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EXTERIOR ILLUMINATION AT THE NEW ZEALAND CENTENNIAL EXHIBITION.

The illumination of the New Zealand Centennial Exhibition was executed by the British General Electric Co., Ltd., of Wellington, the New Zealand branch of the G.E.C. Osram lamps, "Osira" electric discharge lamps and fluorescent tubing were used in conjunction with floodlighting to provide a pleasing variety of colour changing effects.

The illustration shows the General Exhibition Building with the Court of Pioneers in the centre, the 160-ft. Centennial Tower on the left, and the entrance to the main Exhibition Building on the right.

G.E.C. Journal

VOL. XI. AUGUST, 1940. No. 2.

Plastics and the Electrical Industry.

PART II

By A. E. PHIPPS,

G.E.C. Moulded Insulation Works, Witton.

The first part of this article appeared in Vol. X, No. 3 of the G.E.C. Journal, in August, 1939.

In this second part thermo-plastic materials are considered, also the question of the design of moulds and mouldings.

CLASS (b) HOT MOULDED THERMO-PLASTIC MATERIALS.

AS mentioned in Part I of this article, the most widely used thermo-plastic materials are the resin-bituminous compounds, cellulose acetate, polystyrene and methyl methacrylate compounds.

The essential difference between this class, and the class (*a*) or thermo-setting materials, is one of resistance to heat. The difference is fundamental, and the line of demarcation between the two classes is a clear one with no overlapping, at any rate so far as commercial products are concerned. With thermo-plastic materials no chemical reactions take place during moulding, and the heat resistance of the moulded article, is virtually the same as that of the material before moulding, whereas it will be remembered that in the case of the thermo-setting materials chemical reactions take place in the mould, hardening occurs, and the moulded piece has a high resistance to heat, entirely different from that of the original material, in that it cannot be softened again. The fact that the plastic properties of the thermo-plastic materials are substantially unchanged during moulding enables the moulder to utilise scrap and waste material for moulding again, whereas scrap from thermo-setting materials is practically valueless.

A different technique is involved in moulding this class of material, in that the material is softened before entering the mould at such a temperature that when forced into a relatively cool mould it sets very rapidly, and can be ejected in its final form after a short interval of time. This time, termed the "dwell," will vary, of course, with the thickness of the piece, the relative temperatures of the material and the mould, the thermal conductivity of the material and its other physical characteristics.

Two principal methods of moulding are employed. The first, used right from the beginning of the plastics industry, consists of heating the material either on a hot plate or in a mixing machine, placing the required charge in the mould, closing the mould under pressure and ejecting the article after a suitable dwell. This is termed ordinary compression moulding. Closed moulds are more widely employed than flash type moulds. The temperature of the material as charged into the mould will range from 145° C. to 200° C., and the mould temperature from 30° C. to 90° C., according to the nature of the material and the peculiar requirements of the job.

The second method of moulding is termed injection moulding, and consists essentially of heating the material in a chamber or pot, out of which it is forced by pressure of a ram into the mould proper. The diagram (fig. 6) shows the usual arrangement. This method is a development of recent years and was first employed for moulding cellulose acetate, but is also successfully used with other thermo-plastic

materials. It should be added that recently the injection method of moulding has been successfully employed with the thermo-setting materials. A vertical press used for injection moulding is seen in fig. 7.

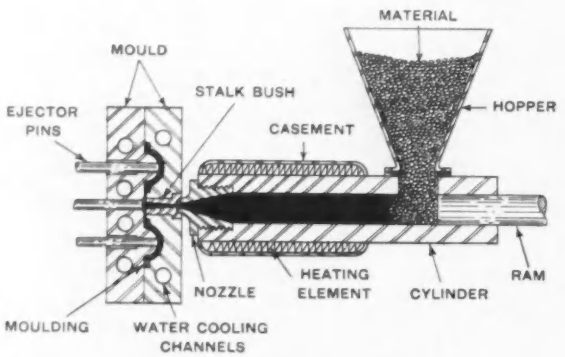


Fig. 6.—Diagrammatic representation of the injection method of moulding.

For thermo-plastic materials the temperature of the pot may range from 100° C. to 190° C., according to the nature of the material being used, and the mould impressions are kept practically cold. As a result the mouldings set extremely rapidly and the rate of production is very high. This represents a very substantial advantage in many cases over compression moulding, in that a smaller number of impressions are required for a given production, with consequent reduction in tool costs. In certain cases, only a fraction of the number of impressions would be needed.

A further advantage is that injection allows the moulding of articles which it is impracticable to make by the compression method. As examples, tubes which are of small diameter and with thin walls in comparison with their length are exceedingly difficult to make by compression owing to the risk of the mould part which forms the tube core bending under pressure, but they can be satisfactorily made by injection. Also, many mouldings which are impracticable by compression on account of the risk of damage to slender mould-pins and complicated or fragile metal inserts can be successfully produced by injection. Fig. 8 shows a typical example of an injection mould with the moulding on the right, while fig. 9 illustrates the moulding in detail and gives a very clear idea of the extreme intricacy of the design.

A third method of moulding is occasionally employed with thermo-plastic materials. This method is a variation of the compression method already described, in that material not sufficiently hot to be plastic is charged into the mould, the temperature of the mould is raised sufficiently to render the material plastic while pressure is applied, but immediately the mould is closed and the article formed, cooling is applied as rapidly as possible so that at the appropriate temperature the article can be ejected without distortion. This method of moulding is obviously slower than injection, and great care must be taken in the design of the moulds to obtain rapid heating and cooling.

As all thermo-plastic materials must have sufficient flow under practical moulding conditions of temperature and pressure to enable good mouldings to be produced, and yet not be liable to deformation under service conditions of temperature and loading, it is obvious that the properties of these materials in relation to temperature have had to be carefully studied. There are two well-known standard tests for this purpose: (*a*) in this country the thermo-plastic yield test of British Standard Specification No. 488, which consists of a cantilever test on a standard bar held at one end and loaded with a standard weight for a specified period of time at a uniform temperature; in which condition the distortion is measured; (*b*) on the Continent the Martens test in which a standard bar of the material is subjected to a bending

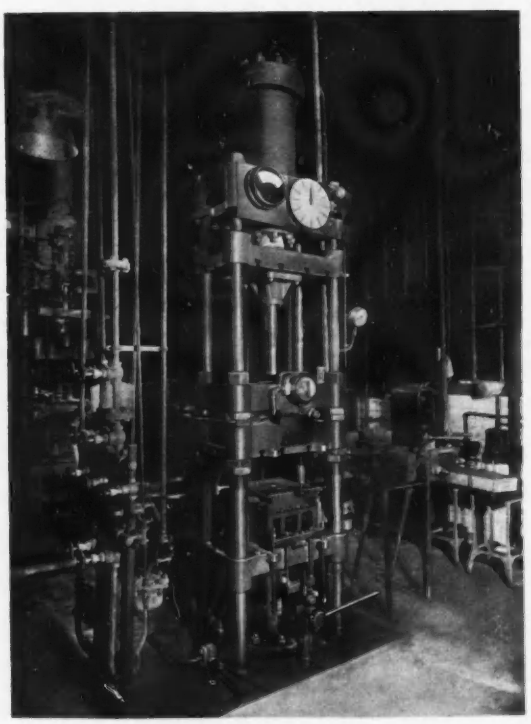


Fig. 7.—Vertical press for injection moulding.

stress by means of a four-point loading device. The specimen held vertical is stressed by means of a weighted lever with a constant bending moment and slowly warmed. The rate of increase of temperature is 50° C. per hour. The plastic yield temperature is

the temperature at which a point on the lever 240 mm. from the centre of the specimen sinks 6 mm.

In this country the standard grade temperature of a material is that maximum temperature at which, under the standard conditions of test specified in British Standard Specification No. 488, the deformation of the bar does not exceed 5 mm. It does not necessarily mean that an article made of that material will stand up to that temperature indefinitely. That depends upon the stresses to which the article is subjected, and the degree of deformation permissible.

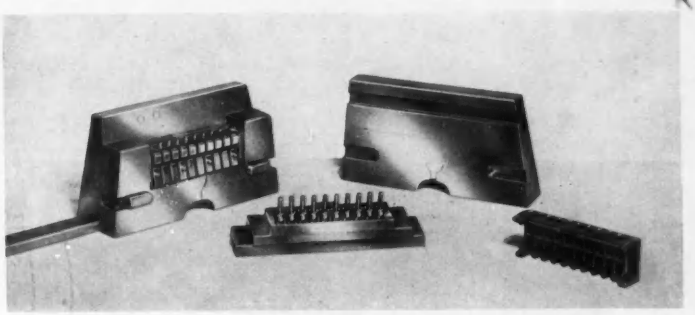


Fig. 8.—Example of portable injection mould with moulding.

The thermo-plastic materials already mentioned differ from one another in chemical composition far more widely than the thermo-setting materials, and their composition and properties will now be dealt with individually and in detail.

Resin-Bituminous Compounds.

Resin-bituminous compounds cover a very wide range of compositions and in the early days of the plastics industry constituted, with the exception of hard rubber, the only materials available for moulding. The various compounds are made by mixing binders such as bitumen, pitch, shellac, colophony, copal and other natural resins either alone or in admixture with fillers such as slate dust, barytes, kieselguhr, etc., fibres either organic, *e.g.*, cotton, or inorganic, *e.g.*, asbestos, being added to give the necessary strength.

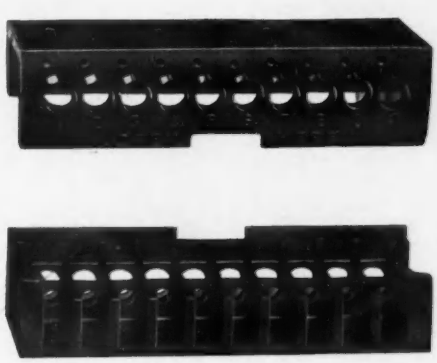


Fig. 9.—Detail view of intricate injection moulding with horizontal holes, produced from the mould seen in fig. 8.

With care in the selection of raw materials and in processing, compounds can be made having excellent electrical properties. By using binders of different melting points, and to a lesser degree by altering the amount and type of filler used, the grade temperature of the compound can be varied, and compounds ranging in grade temperature from 30° C. to 90° C. find commercial applications. The mixing of the compounds is usually done in Pfleiderer type machines at a temperature which will ensure satisfactory mixing but avoid overheating, being usually from 140°C. to 200°C. After mixing, the material is sheeted or tabletted into a form suitable for the reheating for moulding. The moulding process generally used is ordinary compression, but injection moulding is occasionally employed.

During the rapid development of the industry, this class of compounds has been overshadowed and to a considerable degree replaced by the thermo-setting materials. This is due to a number of reasons—low strength compared with the thermo-setting materials, limitations of colour to practically black, dark brown or red, impermanency of finish, indifferent resistance to attack of solvents such as oil, and low heat resistance. Although one, or perhaps two, of these deficiencies could be improved at the expense of other properties by mixing special compounds, it is obvious that the thermo-setting materials with their better properties in all respects would have an instant appeal. Generally speaking, the bituminous materials are now used for those mouldings where the higher cost of other materials is prohibitive, where questions of colour do not arise and a high degree of permanent finish and high heat resistance are not required. Examples are meter terminal blocks, cable cleats, bushes and junction boxes. Special types of these materials are highly resistant to sulphuric acid, and are largely used in the manufacture of accumulator containers.

Cellulose Acetate.

Although, as just mentioned, the introduction of the thermo-setting materials completely altered the picture of the industry by making available materials much superior in almost all properties, high tool costs in relation to production, and lack of toughness still constituted serious handicaps.

The introduction of cellulose acetate made available a moulding material which is exceedingly tough and can be moulded very rapidly by the injection process, with consequent saving in tool expenditure. The articles are produced from the

mould with a good permanent finish, and have excellent mechanical strength. They can be made in an unlimited colour range and are tougher than similar articles in standard thermo-setting materials. Although the heat resistance of these materials is low (30° C—50° C. British Standard Specification No. 488) there are numerous applications where this is of

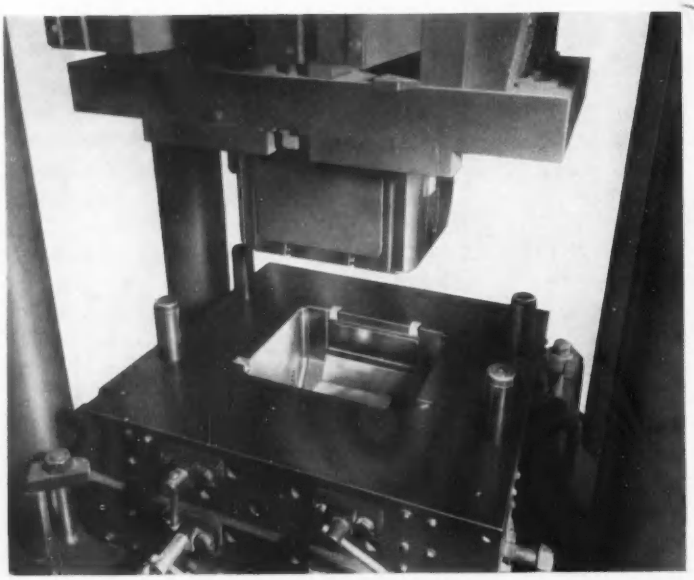


Fig. 10.—A fixed compression mould used for the manufacture of radio cabinets.

no importance. Moreover, very beautiful translucent, mottled, pearl and striated effects unequalled by any other material can be obtained with cellulose acetate. In addition, the advantages already mentioned of the injection method of moulding enabled many articles of intricate shape to be made in this material which hitherto could not be produced by the plastics industry. Automatic injection moulding has been employed very successfully with this material for the manufacture of numerous kinds of articles, special machines having been developed for the purpose. The material is made by incorporating cellulose acetate with suitable plasticisers, fillers, dyes and pigments. The plasticiser is added to give the material satisfactory flowing properties.

Although the electrical properties of cellulose acetate in the dry condition are very good (600—800 v/mil) the water resistance is unfortunately not good, and this fact combined with the low heat resistance has rather restricted its use in the electrical field. Nevertheless, an extensive range of articles is made for the electrical industry, examples being telephone cradles, coil formers, radio grills and knobs, and switch plates.

Methyl Methacrylate Resin Materials.

One of the most recent additions to the available range of thermo-plastic materials is methyl methacrylate. Methacrylic acid is very susceptible to polymerization with the formation of resinous bodies. It was found that the ester methyl methacrylate polymerizes to give plastic products of commercial value. By the incorporation of plasticizing agents with the further addition of pigments, dyes and fillers when necessary, moulding compounds possessing excellent properties can be produced. The moulding properties are very similar to those of cellulose acetate, and both compression and injection methods can be used. As with cellulose acetate, mouldings can be produced in an unlimited colour range, both transparent and opaque, with a good permanent finish, possessing excellent mechanical strength, but having the further advantage that on account of the low affinity of the material for water, the electrical properties are decidedly better than those of cellulose acetate. Although of very recent introduction and undoubtedly capable of further development, it has already found a number of useful applications in the electrical field, despite the fact that the price of the material is high in comparison with the thermo-setting materials and cellulose acetate. As the power factor at radio frequency of this material is very

Fig. 11.—A radio cabinet as an example of a large compression moulding. This cabinet is made in the mould shown in fig. 10.

good, being ·022, and much superior to that of any of the materials mentioned hitherto, it is now being used for a number of applications in the radio field. It is also of interest that the optical properties are very good, the refractive index being 1·50 compared with 1·50—1·61 for Crown glass, and it has been found practicable to mould from it small

lenses for cameras and other optical uses. A suitable grade of this material is produced in sheet form for use in place of glass for windows and cowlings on aeroplanes, and the like.

Polystyrene.

Polystyrene is also a material of recent introduction into the plastics field, although curiously enough it is one of the oldest synthetic resins known to chemists, having been prepared in the laboratory in 1839 by the polymerization of styrene. Without the addition of dyes or fillers the resin is similar in appearance to methyl methacrylate resin, being very clear and resembling glass. Coloured and opaque moulding materials are made as usual by the incorporation of suitable plasticizers, dyes, pigments and fillers. These materials can be produced in an unlimited colour range, and both methods of moulding, compression and injection, can be used to make articles with a good permanent finish and excellent mechanical properties. The behaviour and properties of this material are very similar to those of methyl methacrylate except that the electrical properties can be even better, as the insulating qualities of polystyrene resin are the highest of any available synthetic resin. The power factor at radio frequency is less than ·02 and this makes the material of particular interest to the radio industry. The grade temperature of the material ranges from 50° to 70°C., British Standard Specification No. 488, but by using suitable fillers compounds have been made with much higher heat resistance, but become more difficult to mould as the grade temperature rises. Unfortunately, the present price of the material is high, which militates against its use except in those cases where its exceptional electrical properties justify the extra cost.

Many other thermo-plastic resins are known, for example, the polymers of vinyl esters, but those dealt with in detail constitute the bulk of the production. In comparison with the production of phenol and urea formaldehyde materials, the output of the methyl methacrylate and polystyrene material is small but, as already pointed out, the high cost of these materials to the moulder, being several times that of phenolic materials, restricts their use for very many applications. They are of very recent introduction, are already finding many outlets on merit and not on price and, if, as is usually the case, the prices are successively reduced as output rises, there is every reason to believe that they have a very promising future.

CLASS (c) COLD MOULDED COMPOUNDS.

This class of material was developed before the introduction of the thermo-setting resins to meet the demand, mainly from the electrical industry, for an insulating material which would have a good resistance to heat.

The usual method of producing such materials is as follows: The binding materials, usually bitumen, natural resin or vegetable oils or mixtures of these, are worked up as an enamel by solution in an admixture of suitable volatile solvents. This enamel is then mixed with the usual fillers, such as slate dust, barytes, siliceous earths, etc., and asbestos. The mixed material is used either in sheet form, or as powder, after it has been dried to remove part of the solvents. The moulding is effected in cold moulds under higher pressures than those used for other materials, reaching as much as 5 tons per sq. in. No dwell is required, and the rate of moulding is very high, so that tool costs are kept low. To some extent this advantage is lost on account of the high tool maintenance due to the abrasive nature of the material and the very high pressure. After moulding, the articles are carefully dried out and stoved by slowly raising the temperature to 500/550° F. Well-stoved articles made to correct formula should not soften at high temperatures and should have reasonably good strength, equal to the bituminous plastic materials. Unfortunately it is difficult to maintain a good finish and a certain amount of distortion is difficult to avoid, as the shrinkage on stoving is considerable. The articles can only be made in black, and a certain amount of porosity is un-

TABLE III.

PHYSICAL PROPERTIES OF THERMO-PLASTIC MATERIALS.

	Resin/ bituminous compound	Cellulose acetate	Methyl-methacrylate compound	Polystyrene	Cold moulded compound
Shrinkage (inches per inch) ..	.002ins/.004ins	.002ins/.007ins	.002ins/.006ins	.004ins/.005ins	.006ins/.010ins
Specific gravity	1.2/2.5	1.27/1.40	1.19/1.45	1.05/1.07	1.6/2.0
Tensile strength lbs./sq. inch ..	900/3,500	4,300/7,000	7,500/10,000	5,000/6,000	600/2,000
Impact strength B.S.S. 771 ft./lbs.	0.10/0.30	0.20/0.35	0.25/0.35	.16/.22	
Dielectric strength volts/mil at 20°C. B.S.S. 771	100/400	200/300	200/400	500/525	80/300
Moisture absorption, 7 days ..	0.1/0.6%	1.8/2.5%	0.20/0.30%	Less than .1%	2.0/10.0%
Temperature plastic yield B.S.S. ..	25°/90°C.	30°/70°C.	30°/70°C.	50°C.	Over 120°C.
Colours available	Black and dark colours only	Transparent and all colours	Transparent and all colours	Transparent and all colours	Black only

avoidable with consequent high capacity for moisture absorption. For these reasons, although the material fulfilled a very useful purpose and the production reached very large proportions, the introduction of the thermo-setting materials, which are so much superior in these properties, marked the beginning of the decline in the use of cold moulded materials. At the present time it is confined to those applications where by virtue of low costs and exceptionally good heat resistance, it can be profitably used, for example, for fuse carriers.

DESIGN OF MOULDINGS AND MOULDS.

Frequently moulders are asked to make mouldings which are either unnecessarily difficult to mould, and hence are likely to cause trouble in moulding with consequent poor production, or which call for unduly expensive mould construction. A better acquaintance with certain general principles in connection with the design of both moulds and mouldings would frequently obviate much expense and waste of time.

When the general design of the article has been decided upon there are a number of points which must be considered if satisfactory results and the lowest production costs are to be obtained, although, in practice, it is unfortunately often impossible to incorporate all the desirable features.

Hardened steel is the only really satisfactory material for moulds, and is generally used for the purpose. This is due both to the pressure required for moulding, which may be from 1 to 4 tons per sq. inch, and the abrasive action of the material. In

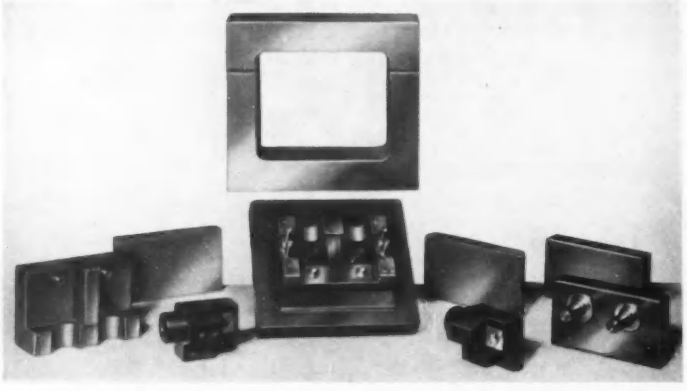


Fig. 12.—Example of a two-impression portable mould embodying splits. The two mouldings are seen in the foreground.

certain cases where the design of a mould may be still the subject of experiment soft steel may be used, since the changes required as the result of experiment can thus be made more easily. For actual quantity production the mould must be hardened.

The moulding surface of the mould must be free from machine marks, and be highly polished. This will reduce the chance of the articles sticking to the mould and, moreover, the gloss on the product will reflect the amount of polish on the mould.

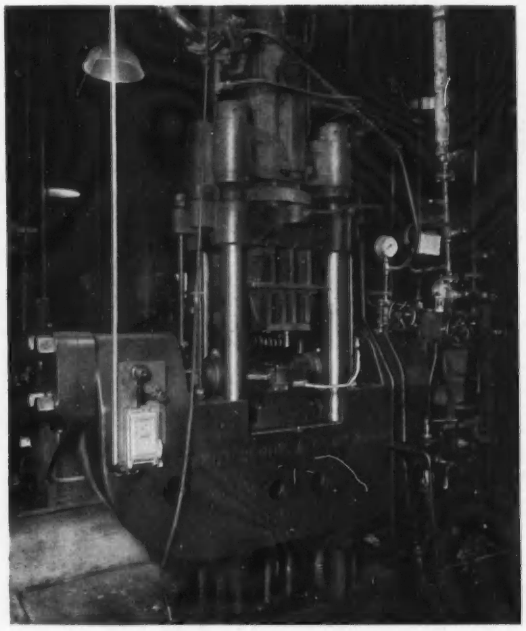


Fig. 13.—Side-cylinder press for compression type moulding, using a split mould.

Moulds may be either portable or fixed. Portable moulds, as their name indicates, are removed from the press after curing to a bench where the operations of opening and extracting the mouldings are effected. The mould is then cleaned, re-charged with material, assembled together and placed back between the platens of the press, which is then closed for a given time until the material is cured.

Portable moulds are used for small articles and usually consist of a single impression, although sometimes if the article is very small it may consist of several impressions. As the mould is constantly lifted in and out of the press its size and weight must be kept within reasonable limits to avoid causing undue fatigue.

Fixed moulds, as the name implies, are secured in the press and are not handled by the operator. Mouldings from fixed moulds are ejected in the press, the operator removing them and cleaning the moulds from dust and flash by means of compressed air. The moulds are then recharged and the press closed.

With fixed moulds larger mouldings can be made and also a greater number of impressions used, with resultant economies. Fig. 10 shows a large fixed type mould used for the manufacture of radio

cabinets, an example of which is seen in fig. 11. It is of interest to note that this moulding is made in the first machine of the battery of presses illustrated in fig. 4 in Part I of this article.[1] Fixed moulds are usually employed for large scale production, special loading and unloading fixtures being used, and the operations of loading and unloading made automatic as far as possible.

When the shape of a moulding is such that it cannot be ejected straight from the mould, such as a bobbin or an egg-cup, then a split mould has to be employed. In this case, the splits are ejected from the body of the mould and opened outside the press, the moulding then being extracted from the splits. Fig. 12 shows a two-impression portable mould of this type. As will be seen, the design of the article is such that this construction is essential. As split moulds usually have to be handled outside the press, articles made by this method involve a longer moulding cycle. If the quantities to be made justify the tool cost, double sets of splits are made so that one set can be in the press curing while the other set is being opened on the bench. Split moulds therefore

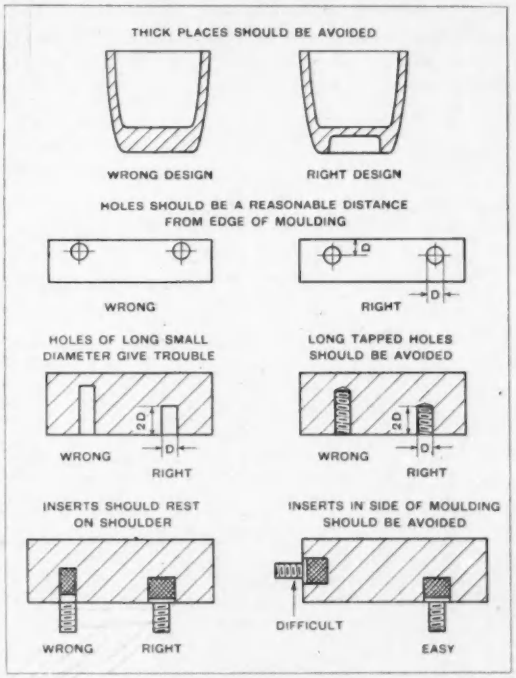


Fig. 14.—Points to be observed in the design of mouldings.

either slow down production or else considerably increase the tool costs. It should, therefore, be the aim of designers to avoid such shapes as would involve this type of mould being used. Where the split type of mould construction is unavoidable for large scale production, special side-cylinder presses are used (fig. 13). Undercuts on the inside of mouldings occasion great difficulty and can generally be regarded as impracticable production propositions, although shallow internal undercuts are produced on bottle caps, where the problem of stripping from the mould is overcome by "jumping," taking advantage of the flexibility of the material while hot.

Metal inserts can be moulded into the insulation material, but it is advisable to consult the moulder on this point, as frequently the introduction of an insert changes what was previously a simple moulding into a difficult, and therefore expensive, article.

If inserts have not to withstand any great strain it sometimes eases the problem if they are pressed into the moulding after its extraction from the mould. This operation is usually performed while the moulding is hot, so that as contraction takes place the insert is securely gripped. The moulder should be consulted as to the advisability of pressing or moulding-in the metal parts.

Sufficient taper must be allowed in designing the moulding to permit of extraction from the mould. For hot moulded articles there should be, if at all permissible, about ·015 inch total taper per inch or ½ degree on each side. Cold moulded articles require much more, about 0·050 inch per inch, on account of the softness and fragility of the moulding as extracted.

Hot moulded articles can with great care be produced to an accuracy of 0·004 inch per inch, cold moulded 0·006 inch per inch on dimensions which are not affected by the closing of the mould. Dimensions affected by the closing of the mould can be produced to a formula which may be expressed as $c + (0{\cdot}004$ inch per inch) for hot moulded articles and $c + (0{\cdot}006$ inch per inch) for cold moulded articles, where c is a constant and may be taken as 0·006 inch. It should be understood that these are fine limits for moulding and greater tolerance should be allowed whenever possible.

It cannot be stressed too strongly that the moulders should be consulted when a moulding is being designed. Considerable expense would often be avoided if this were made a standard practice.

The following suggestions are made in the hope that they will be useful in helping the designer in his effort to evolve a design which will be satisfactory both to the moulder for production and to the user in service (fig. 14).

(1) Avoid undercuts wherever possible. These involve the use of split moulds or loose parts, thereby slowing down production and increasing tool costs.

(2) Do not ask for unnecessarily fine limits. These fine limits add greatly to the technical difficulties of moulding and only lead to a greater percentage of rejections for which ultimately the customer must pay.

(1) G.E.C. Journal Vol. X. No. 3, August, 1939, p. 195.

(3) Mouldings should be uniform in thickness so far as possible, particular care being taken to avoid thin sections in conjunction with heavy walls. The uneven contraction sets up stresses which may result in cracking both in the process of the moulding and in service. The length of cure is determined by the thickest part—an additional reason for avoiding thick, heavy parts.

(4) Avoid horizontal holes as much as possible. In other words, holes should have their axes parallel to the line of pressing wherever possible. Horizontal holes usually have to be drilled, and even if they can be moulded they slow up production in a similar way to splits.

(5) Avoid calling for small holes. A large proportion of the tool repairs in a moulding shop consists of replacing bent and broken mould pins. If possible, keep the depth of a hole less than twice its diameter.

(6) It is difficult to tap holes to a greater depth than $\frac{1}{4}$ inch. It is easy to tap holes up to 2B.A; above this size threads are usually moulded.

(7) The edge of a hole should be a reasonable distance from the edge of the moulding, otherwise cracking may result. Long holes closely spaced and large holes with square corners near an outside surface are objectionable. The edge of a drilled hole should be at least half its diameter from the edge of the moulding.

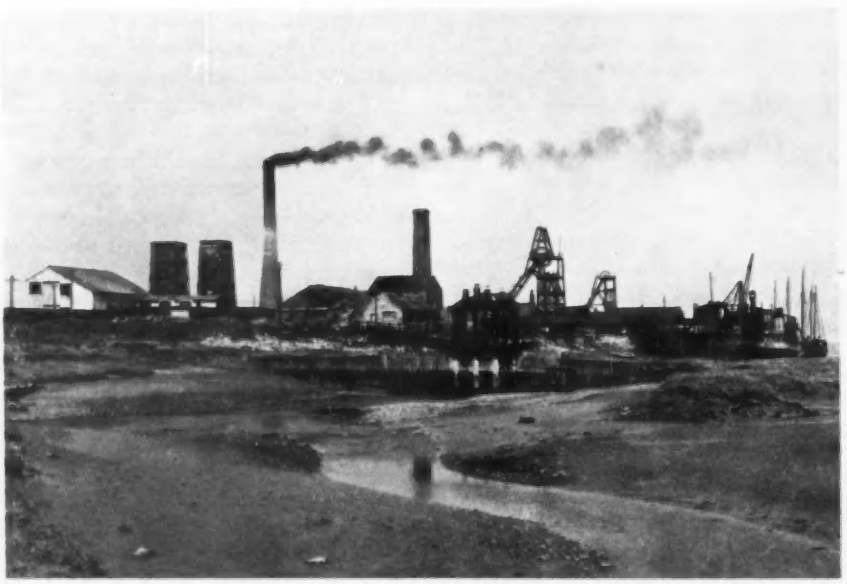
(8) Lettering in relief is much cheaper than sunken lettering filled in with colour. In the former case the mould can be stamped or engraved, whereas the latter, requiring removal of the surrounding metal, is much more expensive. In addition, the raised letters on the mould are easily damaged. Lettering should be arranged on the top or bottom of the moulding, that is from the moulder's point of view; if lettering is required on the side, loose pieces must be used, resulting in slower production and increased tool costs.

(9) It is difficult to mould inserts into the side of a moulding. The moulding pressure frequently shears them off.

(10) Wherever possible, inserts should be provided with a shoulder to take the pressure, and it simplifies the moulding if they protrude from one surface only.

(11) Threads should be as bold as possible. Knurling should be bold and, of course, must be parallel to the direction of removal from the mould.

Electrical Equipment at a British Colliery.



The geographical position of this colliery is unusual as it is situated directly on the coast. The colliery is largely electrified, much of the equipment having been supplied by the G.E.C., including the main turbo-generator and switchboard, a 115 h.p. slipring motor driving a D.C. generator, a 67 h.p. haulage motor, together with a large variety of small motors and control gear in the colliery shops.

Applications of X-Ray Technique to Industrial Laboratory Problems.

By H. P. ROOKSBY, B.Sc., F.Inst.P.

G.E.C. Research Laboratories, Wembley, England.

This article was presented as a paper before the Royal Society of Arts in January, 1940, and was awarded the Silver Medal. It is now reprinted from the Journal of the Society.

The author discusses X-ray crystallography and gives many examples of its practical application in industry at the present time. He illustrates the important fact that, in many cases, X-ray methods yield information unobtainable by chemical means, and that new conceptions of the ultimate structure of matter are arising directly out of recent measurements undertaken in the laboratory.

INTRODUCTION.

THE discovery by Rontgen in 1899 of a new radiation of great penetrating power was the commencement of a new phase in scientific history. Not only has the nature of the radiation itself been of fundamental interest, but X-rays have been the instrument whereby a new and brilliant picture of the fundamental structure of matter has been unveiled. The use of X-rays in medicine is well known to everyone.

X-rays are emitted when matter is bombarded by swiftly moving electrons, and a radiation of wavelength characteristic of the material being struck arises from changes which take place in the inner region of the electron system of the atom. One of the commonest forms of X-ray tube contains a hot filament, usually of tungsten, which is the source of the electrons, and a metal anti-cathode or target. Under the influence of a sufficiently high voltage the electrons are made to impinge upon the target at which the X-rays are excited. In general, the radiation from an X-ray tube consists of two parts, the "white" or continuous spectrum X radiation, and, if the voltage is sufficiently high, the characteristic rays, whose wavelengths depend upon the material of the target. The characteristic emission lines occur in groups known as the K, L, M, etc., series, the K series being the simplest and the shortest wavelength group and practically the most important in crystal analysis. The two individual wavelengths which constitute the K group of an element are usually denoted by the letters α and β; it is possible effectively to remove the β wavelength by interposing a filter of an element appropriate to the radiating element, and so to obtain an essentially monochromatic X-ray beam.

The methods of utilising X-rays fall naturally into two groups depending (*a*) upon their strong power of penetration through various materials, and (*b*) upon their reflection by the regular arrangement of atoms in crystalline substances. The first application can be described broadly as radiography, and the second as X-ray crystallography. It is not proposed to make more than a brief mention of the subject of radiography which deals with the large scale structure or differences in macrostructure of solid bodies; but this article will be concerned primarily with the crystallographic application.

RADIOGRAPHY.

The power of penetration of X-rays which is utilised in radiography depends both upon the kind of substance and upon the quality or hardness of the radiation. The varying resistance of materials to penetration enables a kind of density picture of a complex object to be obtained by irradiating the object with X-rays and examining the emergent beam by means of a photographic plate or fluorescent screen. As an example of the use of radiographic technique, fig. 1 shows a shadow picture of a boiling plate such as is used in a domestic electric cooker. The boiling plate consists of a metal casting containing grooves in which a spiral of nickel-chromium wire is wound and embedded in a cement. In problems connected with the development and manufacture of these plates it is often desirable to ascertain if the nickel-chromium element is correctly disposed within the cement, and this can be quickly done by examination of the radiograph. Another example is connected with the construction of certain types of wireless valve whose electrode systems are contained within a metal anode. Radiographic technique enables the electrode system in the completed valve to be viewed, so that the correct spacing of the parts with respect to one another can be confirmed.

It is perhaps sufficient to mention the importance of X-ray photography in medical diagnosis and in the examination of metal castings for flaws and

inclusions to emphasise that the method has become an indispensable part of our detective equipment. Considerable elaboration of the original simple idea has taken place, and by the choice of hard or soft radiation, the use of filtering devices, improvements

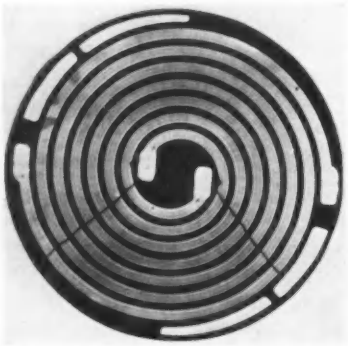


Fig. 1.—Radiograph of boiling plate as used in domestic electric cooker.

in the X-ray tubes, and so on, the scope of the method has been enormously extended.

THE DIFFRACTION OF X-RAYS.

Crystallographers have for numbers of years regarded the external form of the crystal as being connected with the uniformity with which the ultimate units of structure were put together. They postulated the existence of atoms or molecules and it was argued that the mutual reacting forces of these atoms or molecules would tend to produce regularity of structure. Classical crystallography developed an extensive mathematical treatment based upon measurements of the characteristic angles between the crystal faces, and the conception of the space lattice enabled the various symmetry characteristics to be related to a network whose unit eventually became the unit cell of X-ray crystallography.

It is well known that a ruled diffraction grating reflects light falling upon it in certain specific directions which are related to the wavelength of the light and the spacings of the lines of the grating. In order to get diffraction spectra the spacing of the lines must be of the same order of size as the wavelength of the incident light. Laue realised that if X-rays were electromagnetic waves of very much shorter wavelength than ordinary visible light the distances between the atoms or molecules constituting the space lattice of crystals should be of the correct order of magnitude to diffract the rays. Friedrich and Knipping showed experimentally that the prediction was correct and, although Laue's mathematical explanation of the observed effects was somewhat involved, W. L. Bragg arrived at a very simple treatment involving the "reflection" of the rays at planes of atoms a uniform distance apart. If radiation of wavelength λ is incident at an angle θ on a set of atomic planes distant apart d it can be shown that a maximum in the intensity of the reflected wave can only occur if $n\lambda = 2d \sin \theta$ where n is a whole number and refers to the order of the spectrum. The important measurement to be made in crystal analysis therefore is that of θ in the Bragg equation, this equation being known generally as Bragg's law. In certain fundamental work some account has to be taken of slight departures from this law owing to refraction, but this need not concern us here.

The application of X-rays has demonstrated that regularity in atomic arrangement exists in practically all solid bodies. The degree of crystallinity will vary from one solid to another and in some cases only X-rays will demonstrate that regularity of structure exists. The term "amorphous" which has been commonly used in chemical text books for the description of a substance whose crystallinity was not obviously revealed even under the microscope must now be used with caution, and indeed there are very few instances where it can strictly apply. The practical importance of crystal structure will be obvious when it is realised that most of the physical and chemical properties of solids are related to it.

THE POWDERED CRYSTAL METHOD OF X-RAY ANALYSIS.

There are several methods in use for the determination of crystal structure by means of X-rays, but only one of these is widely used in industry for analytical purposes. This is generally known as the

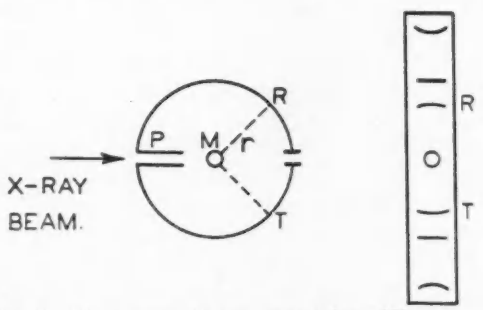


Fig. 2.—Diagrammatic representation of X-ray powder camera.

powdered crystal method, and was discovered independently by Hull in America and Debye and Scherrer in Germany. The powdered crystal method is not generally used by itself for the determination of precise atomic positions, but in most industrial problems it is not necessary to know the actual arrangement of the atoms in the structure provided the substance can be recognised. If the atomic positions are required, resort must generally be made to one of the other methods such as the spectrometer or the rotating crystal method.

If a crystal is broken up into a fine powder we shall have all the atomic planes in the crystal orient-

ated at random. If we irradiate this powder with monochromatic X-rays and consider only one set of atomic planes some of the particles will be in such a position that these planes are at the angle required to reflect the X-rays according to the Bragg law. Again with a second set of planes other particles will be disposed so that reflection takes place, and so on. With an incident X-ray beam defined by pinholes therefore the diffracted rays comprise a series of cones which can be intercepted by a photographic plate in the form of a series of concentric rings. The powder method thus records reflections from the various atomic planes in the crystal at one and the same time. From the geometry of the system used and the Bragg law the distance apart of the atomic planes giving rise to each ring on the photographic plate can be calculated.

Fig. 3.—Powdered crystal photograph of cadmium oxide, CdO.

In practice, for a number of analytical purposes, a modification of the flat plate method is more generally used. A strip of photographic film is wrapped round a cylindrical frame with the powdered specimen on its axis. The powdered crystal may be attached to a glass fibre or hair with an adhesive medium or filled into a thin-walled glass or celluloid capillary tube. Such an arrangement is shown diagrammatically in fig. 2. When the film is unwrapped it has an appearance somewhat similar to that of a spectrum on a spectrographic plate, but the lines are slightly curved as a result of the way in which the diffraction cones are intercepted by the film. A comparatively simple calculation enables values of the ratio of the interplanar spacing to the order of the spectrum, $\frac{d}{n}$ in the Bragg equation, for each line to be determined.

In the diagram the X-ray beam is defined by a collimator P and impinges upon the specimen M. A typical diffraction cone produces lines on the photographic film at R and T, distance S apart.

Then R M T = 4 times the angle of diffraction
$= 4\theta$

If r is the radius of the camera

$$4r\theta = S$$

Combining this with the Bragg equation we obtain

$$\frac{d}{n} = \frac{\lambda}{2\sin\theta} = \frac{\lambda}{2\sin\frac{S}{4r}}$$

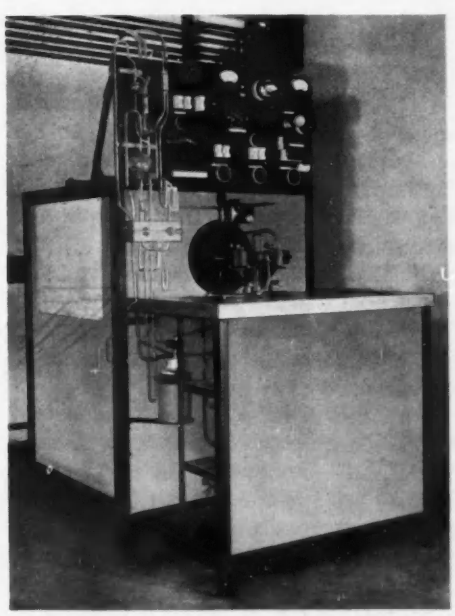


Fig. 4.—X-ray apparatus for recording powder photographs.

By measurement of the distance apart of corresponding lines on each end of the unwrapped film a rapid determination of the distance* apart of the atomic planes with which the lines are associated is made. The calculation involves a knowledge of r, the radius of the camera, but this can be found by calibration of the camera with a substance such as sodium chloride whose interplanar spacings are accurately known. In many modern cameras the value of r is not actually measured. The cameras are so constructed that a knife edge casts a shadow near the high diffraction angle, or as it is often called, back reflection end of the film. The fixed angular position of the knife edge shadow is determined by measurements on an X-ray pattern of a standard substance, and can then be used for the direct determination of the θ values of the lines on the X-ray pattern of the substance whose interplanar spacings are required. Advantages of the device are that difficulties with regard to film shrinkage are overcome, and systematic errors such as are introduced, for example, by eccentricity of the specimen are easily allowed for. The knife edge shadow is also of considerable value when very small changes in lattice dimensions are being observed. This will be illustrated later. A typical X-ray pattern of the kind just described is shown in fig. 3.

Fig. 4 shows a complete X-ray apparatus for the recording of powder photographs. The X-ray tube is of the hot cathode type with a demountable target. The Kα rays of copper are most useful for the kind of diffraction work to be described, but special circumstances may suggest the use of another wavelength, and targets of cobalt, iron, chromium and

* or more strictly the ratio of this distance to the order of the spectrum.

molybdenum are available. The Kα radiation of the elements actually contains two wave-lengths of such small separation that they are only resolved at the higher angles of diffraction. The importance of the α doublet, the usual description of the resolved reflection, will be seen particularly in the discussion of lattice distortion.

It will be convenient to illustrate the use of the X-ray diffraction pattern in industry by referring in turn to those states or attributes of materials which lend themselves to examination by X-ray technique. The headings which have been chosen are as follows :

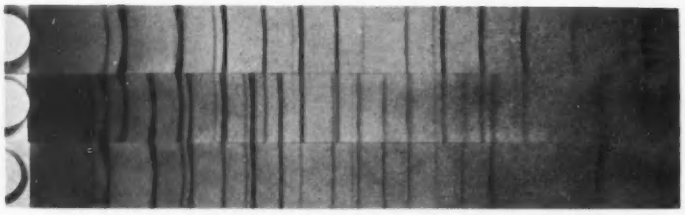


Fig. 5.—X-ray powder photographs showing the identification of sodium chloride and potassium bromide in a specimen containing the elements Na, K, Cl, and Br.

(1) Identification of the chemical compound or compounds present.

(2) Distinction between different crystalline forms of the same chemical compound.

(3) Formation of solid solutions and alloys.

(4) The crystal size or state of subdivision of a material.

(5) The presence of lattice distortion.

(6) Fibre structure.

Naturally in many problems two or more of these conditions may be involved. The refractory materials from which several examples have been chosen are those substances which are of value for work at high temperatures, and include bodies so diverse as the electrical insulators for parts of electronic valves and the materials for building glass melting furnaces. One or two examples have also been taken from the X-ray study of fluorescent substances or phosphors as they are often called. Inorganic luminescent materials are becoming of increasing value in industry, for they have been extensively used for the colour modification and improvement of discharge tube lighting and for the screens of cathode ray tubes.

IDENTIFICATION OF THE CHEMICAL COMPOUNDS PRESENT IN A MATERIAL.

(a) General procedure.

In general each crystalline chemical compound has a unique structure or arrangement of atoms in space, and in consequence it will have a characteristic X-ray diffraction pattern. The uniqueness of the structure and therefore of the X-ray diffraction pattern means that this pattern can be used as an identification mark for the chemical substance. Consequently in conjunction with chemical and spectroscopic analysis we have at our disposal a very valuable weapon for the direct identification of an unknown compound. The chemical or spectroscopic test can be used to show what elements are present ; X-ray diffraction methods will then reveal how these elements are combined. As an example we can take the instance of a material which is known to contain the elements sodium, potassium, chlorine and bromine. By the X-ray method a distinction can be made between a mixture of sodium chloride and potassium bromide, and one of potassium chloride and sodium bromide. Fig. 5 shows the identification of sodium chloride and potassium bromide in a mixture of the two. Moreover, as will be described later, solid solutions of one compound in another can be distinguished from a simple mixture.

The fact that the X-ray pattern depends upon the nature of the compound means that changes of phase, brought about for example by heat treatment, can be followed by the X-ray method. Many instances occur in the study of refractory materials in which X-ray technique has been used to follow the course of changes in the state of combination of the constituents. As an example the determination of the heat treatment to which a mixture of alumina and silica must be subjected to obtain complete formation of the aluminium silicate mullite, $3\,Al_2O_3\,2\,SiO_2$, may be mentioned. No chemical method can give this information since the actual amounts of alumina and silica remain unchanged after the heat treatment. Furthermore, in any one substance several changes of phase may take place on heat treatment at various temperatures. The behaviour of the hydrated aluminium silicate, kaolin, or china clay, an important constituent of many porcelains, on burning at elevated temperatures has been studied by the application of X-ray methods.[1] The stages at which dehydration, break-up into free alumina and silica, and final formation of mullite take place have been found by examining the X-ray patterns of samples of the clay heated to successively higher temperatures.

The method of identification, of course, implies an extensive knowledge of the types of X-ray pattern which are likely to occur, but in a given subject the expert may soon acquire sufficient familiarity to recognise a pattern at a glance. Certain aids to this recognition are available ; for example, crystal structure data are now so extensive that sometimes measurements can be made on the unknown pattern, and comparison with the established lattice constants

of several likely compounds will then reveal the identity of the unknown substance. Further, the type of pattern can often be recognised as being associated with members of a certain crystal class—most patterns from crystals of cubic structure are unmistakable—which limits the search. An instance of the use of this kind of technique is that of a sample of an ore which was being examined in connection with an investigation of its separation by mineral flotation. The ore was said to contain the cobalt arsenide mineral, smaltite, $CoAs_2$, but some difficulty had been experienced in arriving at satisfactory chemical analyses. If the chemically determined cobalt was calculated to $CoAs_2$, a deficiency in the total assay figures was at once evident. When the mineral was examined by the X-ray method, the X-ray pattern was at once recognised as that of a compound of cubic structure, and the calculation of the lattice dimensions showed it to match the established data for the cobalt arsenide mineral skutterudite, $CoAs_3$, and not smaltite. Correction of the method of calculating the cobalt arsenide then enabled satisfactory assay figures to be arrived at.

Some workers in America[2] have attempted to classify data on X-ray diffraction patterns in terms of interplanar spacings in the hope of arriving at a rapid method of identification somewhat analogous to the identification of the lines on a spectroscopic plate from tables of wavelengths. Keys were made of powder diffraction data for 1,000 chemical substances and an index made which could be rapidly referred to. The main criticism of the method appears to be that it is practically impossible to confine our attention to only 1,000 substances; the unknown has an unfortunate habit of being the one-thousand-and-first substance which has not been listed.

(*b*) *Examination of small amounts of material.*

It frequently happens that there is only a very small quantity of material available for examination, insufficient for a chemical analysis. The X-ray method is peculiarly suited to problems of this nature and moreover it is possible to arrange that the actual sample is not destroyed. Such analyses as those of deposits which may be formed in various vacuum devices, of the products of oxidation of the metals constituting electrical heater elements, or of the products of corrosive action on metals can be carried out by X-ray means. In the manufacture of a gas-filled or vacuum lamp, for example, the accidental introduction of extraneous matter or the contamination of the components may result in the formation of a deposit on the glass bulb. There is generally insufficient material for chemical examination, but the compound can usually be identified by X-ray methods, and so the source of the trouble located. In this way it has been found that a deposit of tungsten nitride is formed in the presence of nitrogen, whilst the complex effect of traces of water vapour may result in finely-divided metallic tungsten being carried to the bulb and in very early failure of the lamp.[3]

Another example of the examination of a small quantity of material deals with the conditions at the surface of the core of the cathode used in wireless receiving valves. The emitting cathode consists of a nickel wire or tube with a coating containing the

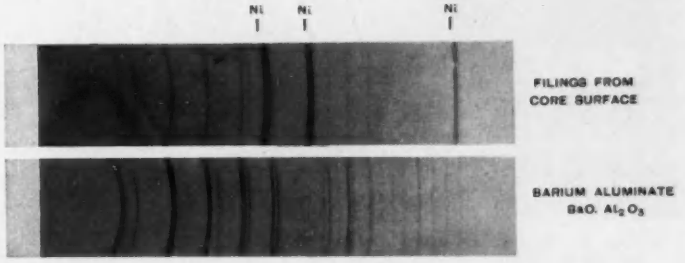


Fig. 6.—X-ray powder photographs showing presence of barium aluminate on core surface of thermionic cathode after activation.

oxides of barium and strontium. For a complete understanding of the mechanism of emission it is of interest to know what reactions take place at the coating/core interface. Small quantities of elements such as aluminium and magnesium are often alloyed with the nickel as these have been found to facilitate the process of forming the emission or activation as it is sometimes called. Any interfacial film which may result from chemical reaction between coating and core will be extremely thin, so that ordinary chemical methods of examination are not possible, but X-ray technique can be devised whereby the nature of the film can be established. It has been shown, for instance, that with a nickel core containing a small amount of aluminium of the order of two per cent by weight, the compound barium aluminate $BaO.Al_2O_3$ is formed, although the coating contains both barium and strontium oxides. This is illustrated in fig. 6 where an X-ray pattern of carefully prepared filings from the core surface of such a cathode after activation is compared with that of barium aluminate. With a nickel core containing magnesium, magnesium oxide has been detected at the coating/core interface after similar treatment. Both the alumina necessary for formation of the aluminate and the magnesia evidently result from reduction of the barium oxide in the coating by the aluminium and magnesium additions to the nickel, and thus the barium necessary for the thermionic activity of the coating is more readily freed than when pure nickel is used as the core material.

(c) *Opal glasses and crystalline inclusions in glass.*

Another type of problem which can be suitably investigated by the X-ray method concerns crystalline material which is difficult or impossible to separate from the medium in which it occurs. For example, in opal glasses there are spherical particles which give to the glass its peculiar property of scattering light, but these particles cannot be removed for analytical purposes, and any direct analysis of the glass by spectroscopic or chemical methods is of little value so far as the nature of the particles is concerned. The X-ray pattern of a glass is little more than a diffuse band, so that if the particles in the opal glass are crystalline a sharp line diffraction pattern superimposed on a diffuse background will be obtained for the opal glass and enable the particles to be identified. The X-ray pattern of an opal glass does show these sharp lines and the results of examination reveal that in a large class of opal glasses the particles are sodium fluoride or calcium fluoride or a mixture of these. Before the X-ray method was used no definite conclusion as to the composition of the particles had been reached.[4]

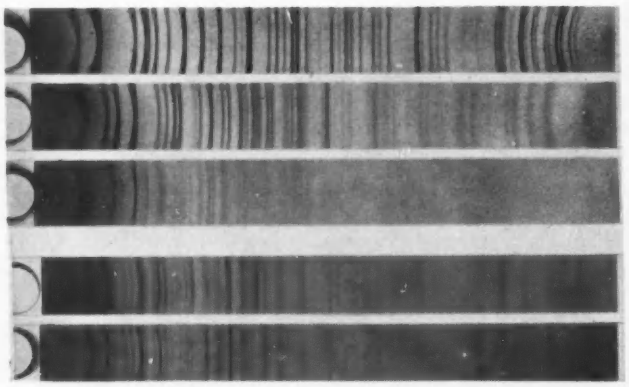
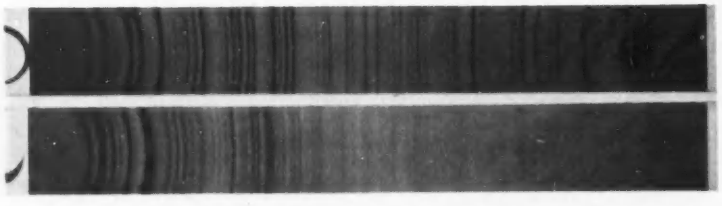


Fig. 7.—X-ray powder photographs of the three crystalline forms of silica stable at ordinary temperatures, and of burnt fireclay showing residual α quartz in poorly fired material.



(*a*) Green fluorescent zinc silicate. (*b*) Yellow fluorescent zinc silicate.

Fig. 8.—Fowdered crystal photographs of two forms of zinc orthosilicate.

The diffuse nature of the X-ray pattern of a glass also enables us to detect in it quite small quantities of a crystalline phase which may be produced, for example, by holding the glass at some specified temperature for a long period. The X-ray method has been used extensively for the identification of this devitrification product, as it is often called, and although the microscope is an important alternative instrument for this purpose, in some instances only the X-ray pattern can give the information required. When the X-ray pattern is identified I think it is true to say that the result is more positive than a diagnosis with the microscope. In the manufacture of glass articles such as are used for domestic purposes crystalline matter sometimes appears in the form of small "stones." These not only detract from the appearance of the glass, but may be the cause of premature failure, and naturally their occurrence must be stopped as quickly as possible. The crystalline inclusions may be the result of devitrification, or they may be derived from refractory material which has broken away from the walls of the melting tank, or they may consist of one of the original constituents such as silica which has failed to go completely into solution. For any given glass the composition of the stones will be dependent upon the cause from which they arise, and the X-ray method can be used to reveal this composition so that any adjustments which may be necessary for the elimination of the stones are made with a knowledge of their source.

DISTINCTION BETWEEN DIFFERENT CRYSTALLINE FORMS.

In the examples which have just been described we have been concerned with the direct identification of the chemical substance as such, and have not considered the occurrence of a substance in more than one crystalline variety. Discussion of allotropic modifications occurs in chemical accounts of many of the elements such as sulphur or phosphorus but the various forms mentioned are not always distinct crystalline varieties. Since the X-ray pattern is directly dependent upon atomic arrangement, where there are real differences between the atomic arrangements of two varieties of a substance these varieties can be clearly distinguished. It is quite obvious that chemical methods are unavailing since the different crystalline forms have one and the same chemical formula. It is possible in some instances to distinguish the crystalline modifications by measuring some physical property such as co-efficient of expansion, electrical resistance, or refractive index, but such measurements

are generally less sure and direct than the X-ray method, and when the specimen available is small or is embedded in some other material the measurements may be extremely difficult, if not impossible.

One of the most important instances of a compound occurring in more than one crystalline form is that of silica. X-ray diffraction patterns are shown in fig. 7 of the three crystalline forms of silica which can be obtained at ordinary temperatures, α quartz, α cristobalite, and α tridymite. These are of considerable interest in connection with the refractory bodies used in the glass and steel industries. Many of these refractory bodies are made with clays which contain in the raw state more or less α quartz. Quartz is changed to cristobalite or tridymite on firing to temperatures above 1000°C., and it is essential that the final condition of the refractories after the firing treatment received during manufacture is such that the whole of the quartz has been converted to cristobalite and tridymite. X-ray examination is made to assess the quality from this point of view. The presence of quartz adversely affects the life of the material under furnace conditions, since considerable strains are set up as a result of the volume change which takes place when the quartz changes to cristobalite or tridymite in the hotter regions of the furnace. Below the silicas in fig. 7 are shown the X-ray patterns of a typical siliceous refractory which is in a poorly fired condition, and one which has received adequate firing treatment. The second phase in these X-ray patterns is the aluminium silicate, mullite.

As a second example of the distinction between different crystalline modifications the X-ray examination of samples of alumina prepared in different ways may be mentioned. Alumina is of great importance in the preparation of insulators for a number of purposes in the electrical industry, and the common form, corundum, is the main constituent of such precious stones as ruby. The existence of two crystalline varieties of the trihydrate of alumina, two of the monohydrate, and two of the anhydrous form is demonstrated by the X-ray patterns.[5]

In the study of fluorescent materials it is found that different fluorescent colours are sometimes associated with a change in the crystalline form. A typical instance is that of zinc orthosilicate whose fluorescent colour is usually green, but which under special conditions of preparation has a yellowish fluorescence. The X-ray patterns, fig. 8, demonstrate that the colours are associated with two different crystal forms. It may be of some interest to note here that the X-ray pattern has been used as an identification mark in filing a patent claim[6] for the second variety of fluorescent zinc silicate. I think I am correct in stating that this was the first use of X-ray diffraction measurements for identification purposes in patent literature.

THE FORMATION OF SOLID SOLUTIONS OR MIXED CRYSTALS.

When metallic copper is alloyed with metallic nickel random replacement of atoms on the nickel space lattice by copper atoms takes place. The dimensions of the space lattice of the alloy are intermediate between those of nickel and copper, owing to the difference in size between the atoms, and depend upon the ratio of nickel to copper atoms present. Nickel and copper are completely soluble one in the other and a series of alloys containing different proportions of nickel and copper is the simplest instance of solid solutions or mixed crystals. The changes in lattice dimensions can naturally be followed by X-ray analysis, and in many instances these changes are found to follow closely a linear law with changes in atomic composition. Fig. 9 shows the X-ray patterns of two alloys of nickel and copper compared with those of the pure metals.

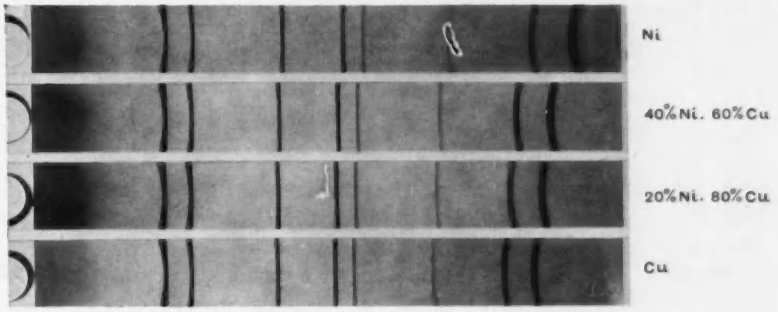


Fig. 9.—X-ray powder photographs of nickel-copper alloys.

Apart from metallic alloys, mixed crystals or solid solutions are most frequently formed by compounds having similar crystal lattices which only differ in dimensions. With compounds a linear law connects changes in lattice dimensions with changes in molecular composition to a fair degree of accuracy, so that the composition of a solid solution phase can be determined by measuring the displacement of its X-ray pattern from the X-ray patterns of its components. Such solid solutions are formed between the compounds barium carbonate and strontium carbonate which constitute the undecomposed condition of the oxide coating of the cathodes of wireless receiving valves. The difference between the X-ray patterns of a mechanical mixture of the two carbonates and the solid solution containing approximately fifty molecular per cent of barium carbonate is shown in fig. 10. Accompanying these X-ray patterns are those of two cathodes after decomposition of the

coating. These cathodes were originally coated with a mixture of carbonates and the mixed crystal carbonate respectively, and it will be seen that whilst for the first the coating is a mixture of barium and strontium oxides, a single phase which is a solid solution of barium and strontium oxides has been produced on decomposition of the carbonates in solid solution form. It is found that for maximum thermionic activity the coating must be in solid solution form, and that it is essential to use a carbonate of the solid solution type to ensure that the correct oxide condition is obtained. Another aspect of the problem is concerned with the behaviour of the oxide coating on running the cathode for a considerable time at a high temperature. The results of X-ray examination show that a preferential loss of barium oxide accompanies a reduced emission, the loss being measured by the change in composition of the mixed oxide.[7] By such direct measurements of coating composition the range of temperature can be determined over which the cathode operates without prohibitive loss of barium oxide.

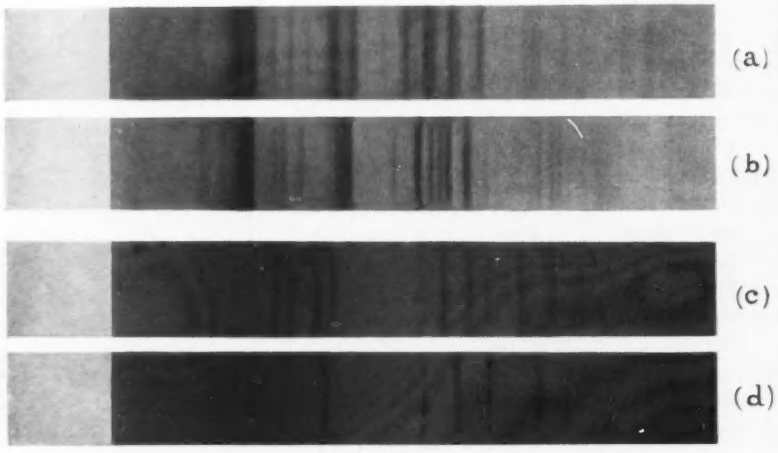


Fig. 10.—X-ray powder photographs of thermionic cathode coatings.

(*a*) Mixture of $BaCO_3$ and $SrCO_3$.
(*b*) Solid solution of $BaCO_3$ and $SrCO_3$.
Prepared by co-precipitation.
(*c*) Coating consisting of mixture of *BaO* and *SrO* (low emission).
(*d*) Solid solution *BaO*/*SrO* coating (high emission).

Perhaps one of the most interesting instances of a continuous series of solid solutions is that of the luminescent zinc/cadmium sulphides. Members of this series are used extensively in the manufacture of the screens of cathode ray tubes, and for colour modification of certain mercury vapour discharge lamps. The effect of solution of cadmium sulphide in zinc sulphide is to displace the green fluorescent band associated with zinc sulphide towards the red, so that materials with a wide range of fluorescent colours from blue-green, through yellow, to orange and red can be made by altering the ratio of cadmium sulphide to zinc sulphide. The changes in molecular composition can be followed by the X-ray method, and fig. 11 shows the X-ray patterns of zinc sulphide and cadmium sulphide and several members of the solid solution series. The solution of cadmium sulphide in zinc sulphide causes an expansion of the zinc sulphide lattice, and a linear law connecting the change in molecular composition with the changes in lattice dimensions is closely followed. The X-ray method for determining the composition of the solid solution phase has been found to be accurate to one or two per cent, and one of its important advantages in the control of manufacturing technique is that the composition determined is actually that of the sulphide and is not affected by the presence of oxide, for instance, which may have been formed in the manufacturing process. One other feature of the X-ray measurements may be mentioned. New fluorescent colours are often obtained by blending two zinc/cadmium sulphides of different compositions, but a chemical analysis will not reveal when this has

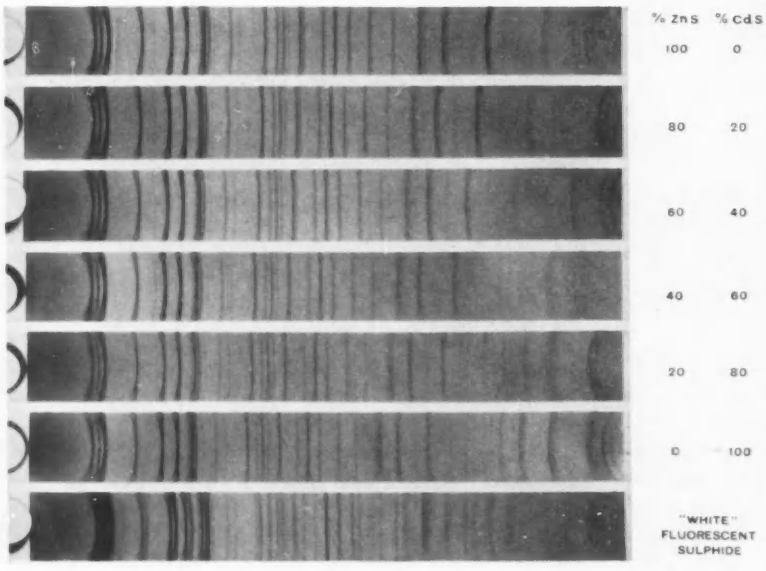


Fig. 11.—X-ray powder photographs of series of luminescent zinc/cadmium sulphides.

been done. The X-ray method enables the composition of both phases to be determined, as each phase will show up separately on the X-ray pattern.

The measurement of solid solution effects is not confined to those instances in which comparatively large changes in lattice dimensions take place. If the back reflection end of the pattern is used quite small effects can be demonstrated by comparison of the displacements of the lines from the knife edge shadow. An example of this kind of measurement is connected with the investigation of the function of activators in luminescent compounds. Many phosphors are only fluorescent when a small amount of impurity is incorporated during the preparation. Manganese is an impurity which is used very extensively and its position in the lattice of the matrix material has been discussed from time to time. It has been possible, by X-ray examination, to demonstrate for several phosphors that the manganese replaces one of the atoms of the matrix lattice. Fig. 12 shows that the zinc orthosilicate lattice for instance, is expanded in the presence of manganese, the lines in the X-ray pattern of the phosphor being displaced further from the knife edge shadow than those in the X-ray pattern of the pure zinc orthosilicate. The phosphor is in effect a solid solution of manganese orthosilicate in zinc orthosilicate.[8] Changes in lattice dimensions of a few parts in ten thousand can be measured in this way.

Fig. 12.—X-ray patterns of (a) zinc orthosilicate pure; (b) zinc orthosilicate phosphor containing manganese.

THE MEASUREMENT OF CRYSTAL SIZE.

Hitherto we have dealt mainly with the question of identification and have not been concerned with what may be termed the texture of the material. We have assumed that the substance examined is in the form of a fine powder, or at least contains enough small crystals to give continuous rings or lines on the X-ray pattern. This is only strictly true if the average crystal size is below 10^{-3} cms.; as the size becomes larger than this figure the rings commence to break up and show the individual reflections from the crystal planes. This fact can be made use of for the investigation of the effect of firing treatment on crystal growth or determining the stage at which recrystallisation takes place in a metal. As an example of the kind of changes which take place fig. 13 shows the X-ray patterns of various quartz sands of different crystal sizes.

The technique has been used to prove that in the very purest refractory substances obtainable the crystal size is related to the temperature of firing. It is well known of course that the presence of certain impurities does aid crystal growth and fluxes are deliberately added in many instances, but in some refractory insulators extremely pure components are used and the mechanism of the toughening on firing is not clear unless it be assumed that inter-crystalline growth does take place in the absence of impurities. The X-ray patterns of the purest magnesia available after firing at 1,100°C. and 1,700°C. respectively reveal a marked difference

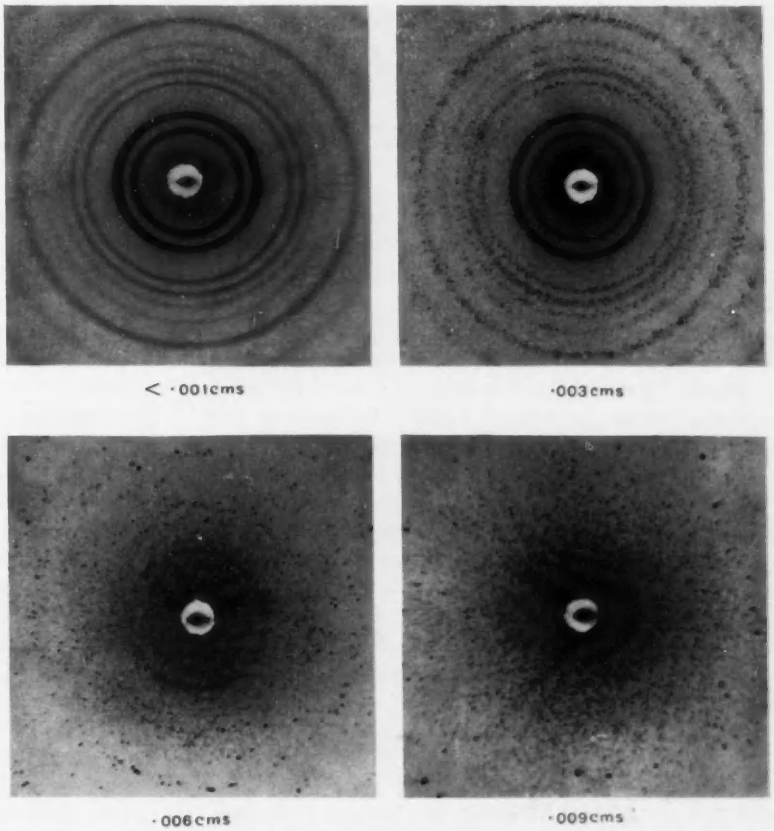


Fig. 13.—X-ray patterns of powdered quartz crystals of different ultimate particle sizes.

in crystal size, and similar results are obtained with pure alumina.

By suitable calibration of the X-ray patterns it is possible to use the method to obtain a value of the average crystal size in a given specimen. This involves usually a measurement of the average size of the individual diffraction spots on the X-ray pattern which increases with increasing crystal size.

We must now consider the result of decreasing the average crystal size of a powder. We have indicated that for the formation of continuous sharp rings on the diffraction pattern the particle size of the powder should be below 10^{-3} cms., but if the size is decreased too far a notable change in the sharpness of the lines take place. Below a size of approximately 10^{-5} cms. a broadening of the diffraction lines is observed, and for very small crystals the lines may become so broad that a more correct description is to speak of diffraction bands. Fig. 14 shows the X-ray patterns of a group of magnesium oxides prepared by decomposition of magnesium carbonate at successively decreasing temperatures, and the broadening of the diffraction lines with reduction in size of the magnesium oxide particles is quite obvious. The cause of the broadening can be regarded as similar to the cause of the increase in angular width of spectral lines when the number of lines in a diffraction grating is too small. Several formulae have been given relating line width and crystal size, and one worked out by W. L. Bragg and co-workers applying to crystals of simple cubic structure is

$$B = \frac{0{\cdot}9\lambda}{t \cos \theta}$$

where B is the width of the line measured to half intensity, t is the size of the crystallites and θ the angle of diffraction.[9]

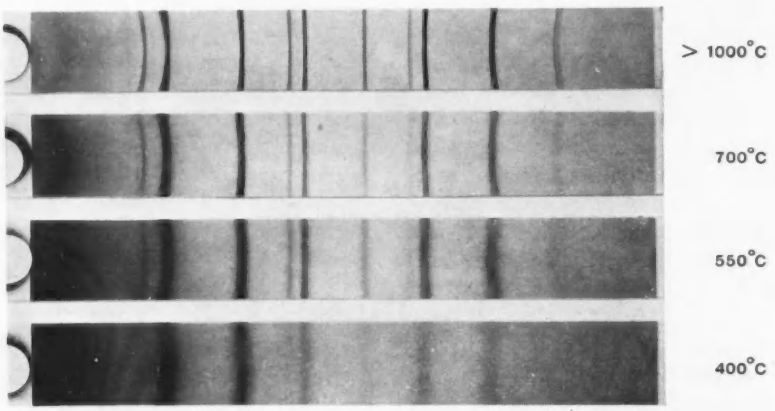


Fig. 14.—X-ray powder photographs showing increase in line width with decrease in crystal size of magnesium oxide. The specimens were prepared by decomposition of $MgCO_3$ at successively lower temperatures.

One of the most interesting examples of the examination of substances of small crystal size is concerned with the relation between "amorphous" carbons such as blacks or cokes and graphite. The X-ray examination shows that all so-called "amorphous" carbons can be regarded as degenerate forms of crystalline graphite; that is, they contain very small crystallites of graphite, the average size depending upon the source and method of preparation. Fig. 15 shows the X-ray patterns of a series of cokes which have been formed from pitch at different temperatures. The decrease in band width with increasing temperature of formation should be noted, whilst the similarity in the position of the diffraction bands of the cokes with the position of the strongest lines in the pattern of graphite shows that the cokes consist of finely-divided graphitic particles.

One point of practical importance in connection with the examination of the cokes may be mentioned. In some manufacturing processes it is often necessary to determine what effective heat treatment has been given to a sample of coke or "amorphous" carbon. It is found that the ultimate particle size of "amorphous" carbon depends more upon the actual temperature of heat treatment than upon any other factor, so that the temperature to which a given sample has been heated can be ascertained with reasonable accuracy by comparison of its X-ray pattern with those of the standard series of cokes.

THE PRESENCE OF LATTICE DISTORTION.

When a metal is deformed or cold worked as in the process of drawing wire or rolling sheet two effects may be immediately observed. The original grains or crystals are broken up into smaller units and at the same time the lattice is distorted from its normal dimensions and lattice strain is set up. It

has been shown that the break-up of the crystal fragments does not go on indefinitely, but a lower limiting value of the crystal size is reached, which may vary from one metal to another, but is of the order of 10^{-4}cms.[10] The value of the minimum crystal size is not sufficiently small to result in much broadening of the diffraction lines on the X-ray pattern, but in fact in the pattern of a deformed metal the lines are diffuse. The broadening of the lines is associated with the lattice distortion and is explained if it is supposed that the mean lattice dimensions vary from one crystallite to another. The broadening is best observed at the back reflection end of the X-ray pattern, and in many instances the distortion is sufficient completely to smooth out the α doublet into one diffuse line. Fig. 16 shows back reflection X-ray patterns of cold worked nickel compared with the undistorted metal. Accompanying the broadening there is a reduction in the intensity of X-ray reflections, and many investigations on lattice distortion make use of this effect instead of the broadening effect.[11] It has also been shown that the mean dimensions of the distorted lattice are slightly greater than those of the undistorted lattice. The lattice strain can be completely removed by heating the deformed metal to a given temperature which varies from one metal to another; the resolution of the α doublet is restored and the metal is said to be in the annealed condition. The process of annealing should be distinguished from that of recrystallisation or the stage at which crystal growth begins; the temperature of annealing at which recovery of the resolution of the X-ray reflections is obtained is generally well below that at which definite signs of crystal growth occur.

One possibility of using the lattice distortion phenomena for practical purposes will be indicated. As will have been gathered from the discussion on crystal size measurements, information is often required concerning the heat treatment to which a given material has been subjected. The release of lattice strain will be a function of both the time and temperature of annealing. If the time of annealing is kept constant it should be possible to use the degree of restoration of the resolution of the α doublet in the X-ray pattern to indicate the temperature of heat treatment of the metal. Fig. 17 shows a series of X-ray patterns illustrating the effect of heat treatment for five minutes at various temperatures on deformed tungsten, the specimens being the untreated coiled coil filaments used for the manufacture of gas-filled lamps. The increase in resolution of the α doublet with increase in temperature of heat treatment should be observed.

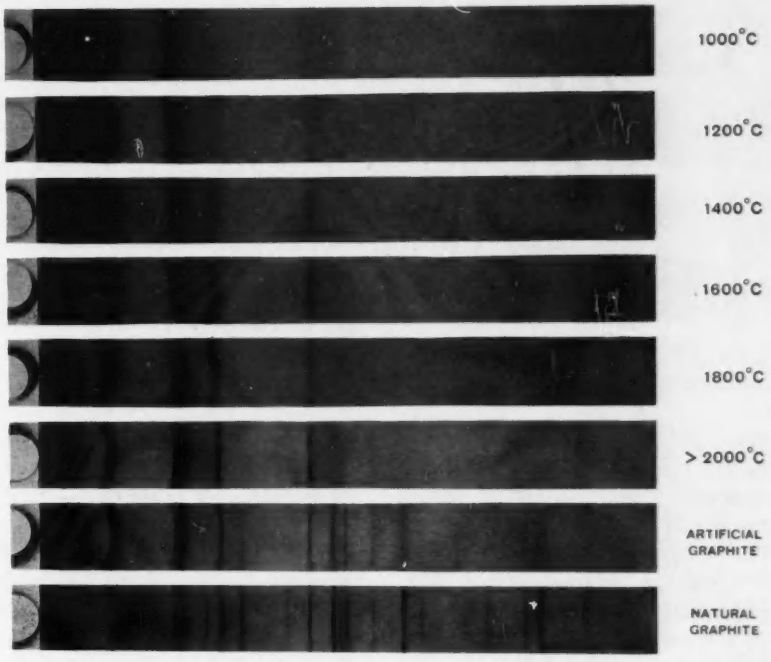


Fig. 15.—X-ray powder photographs showing increase in size of graphitic crystallites in cokes formed from pitch at successively increasing temperatures.

FIBRE STRUCTURE.

There is yet a third change brought about in a metal as a result of deformation by the mechanical processes necessary to produce wire and sheet. The break-down of the original crystal grains in the

metal is accompanied by slip along the more weakly bonded atomic planes and a rotation of the crystallites takes place which eventually brings the strongest axes of the crystals into alignment with the direction of working. This means that in a drawn wire the crystals have a particular crystallographic axis parallel to the wire axis; such an orientation produced by cold work is often called the preferred orientation.

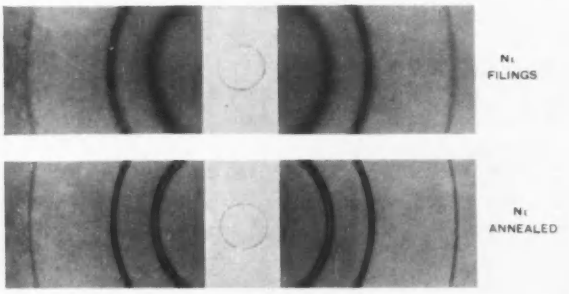


Fig. 16.—X-ray back reflection photographs showing lattice distortion in metallic nickel deformed by filing.

It will be remembered that the condition for obtaining continuous rings on the X-ray powder photograph is that the crystals in the powdered specimen should be disposed at random. If the crystals are orientated in a particular way, as in a drawn wire, when the incident X-ray beam travels in a direction perpendicular to the wire axis the diffraction rings will no longer be continuous but will be concentrated into certain special directions. The wire specimen behaves very like a single crystal rotated on one of its axes. The development of preferred orientation by rolling a metal into sheet is very similar, except that the crystals tend to align themselves not only with respect to the direction of rolling, but also to the plane of rolling. Typical fibre diagrams for rolled sheet are shown in fig. 18. The photographs were taken with the X-ray beam travelling in a direction perpendicular to the plane of the sheet. The difference in appearance between the two diagrams is related to the difference in crystal structure; molybdenum has a body-centred cubic lattice whilst aluminium has a face-centred cubic lattice.

The significance of the orientation of the crystals developed in rolled sheet can be seen from the following example. In the manufacture of molybdenum sheet which is used for the metal anodes of certain types of wireless valve a rolling procedure is sometimes adopted in which the direction of rolling is turned through a right angle after a partial reduction in thickness of the original ingot. A peculiar type of brittleness then develops in the finished sheet after the final annealing treatment. The sheet is particularly weak in directions at 45° to the directions of rolling. When the crystal orientation in such molybdenum sheet is examined by X-ray methods it is found that the completely preferred condition exists, and cleavage planes or cube faces are at 45° to the directions of rolling and at the same time perpendicular to the surface of the sheet. A thin layer cut from a single crystal of molybdenum parallel to one of the cube faces would be equivalent to the conditions in the cross rolled sheet, apart from the absence of grain boundaries. This type of brittleness is not experienced with sheet prepared by rolling continuously in one direction since there is found to be considerable deviation from the ideal preferred condition about the direction of rolling.[12]

The investigation of fibre structure is not confined to metals. Much work has been done on organic substances such as artificial and natural silk, cotton, and rubber where in many instances the degree of alignment of the minute fibres may affect the strength of the thread. The fibre diagrams, in view of their relation to rotation photographs of single crystals about a specific axis, have contributed to an understanding of the structure of the crystallites constituting such organic materials.

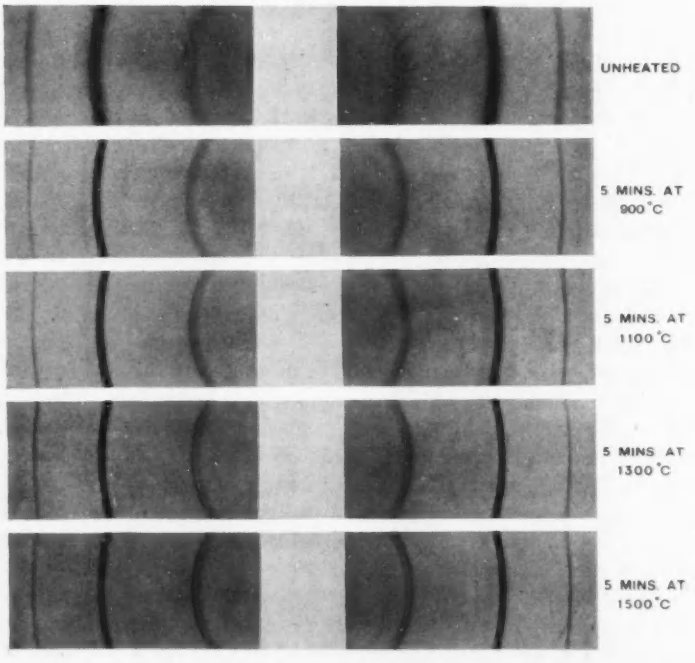


Fig. 17.—X-ray back reflection photographs of coiled-coil tungsten lamp filaments after heat treatment at various temperatures.

CONCLUSION.

I have attempted in this paper to give some idea of the various ways in which the X-ray crystallographic method of examination has been used in an industrial laboratory, but I do not suggest that the treatment has been by any means exhaustive. Many of the illustrations chosen have emphasised how X-ray methods give information which cannot be obtained by chemical means, but there is no doubt that the most instructive solution to a problem is reached only by utilising all the methods of investigation at our disposal. The complementary nature of the information given by X-ray, chemical, and spectroscopic methods of examination has been mentioned; in many metallurgical problems the results of microscopical examination can be amplified and elaborated by X-ray analyses; in assessing the quality of refractory materials the X-ray tests take their place alongside measurements of porosity, thermal expansion, extension under load, and so on. We must also envisage the addition of new instruments to reveal yet further properties of materials, and the method of electron diffraction may be mentioned as being better suited to the examination of surface phenomena than X-ray analysis. On the other hand, it is not always realised how wide is the scope of X-ray analysis, and how certain physical properties such as coefficient of expansion which have been measured in the classical manner have also been measured by X-ray methods. Such new measurements should not be regarded merely as repetitive, for new aspects of the physical property may be revealed by a fresh method of approach.

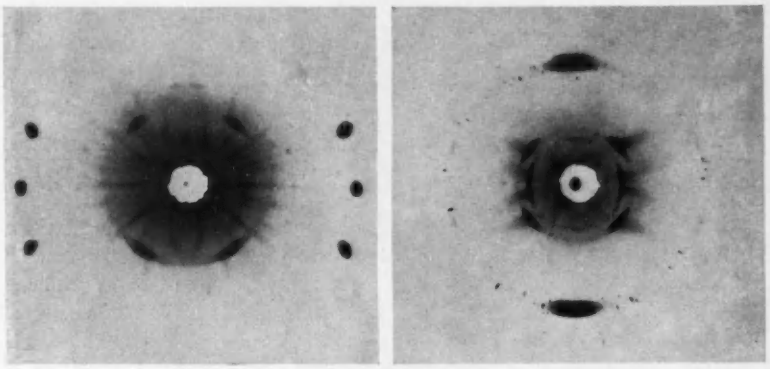


Fig. 18.—Fibre photographs showing preferred orientation in rolled metal sheet.

Finally, we must not omit mention of the contribution that X-ray analysis is making to our fundamental ideas of the structure of matter. New conceptions are arising directly out of the recent measurements on lattice distortion and the lower limiting size of crystallites developed in a cold worked metal, and the gradual clarification and development of our picture of the ultimate structure of matter owes much, and will owe still more in the future, to the revealing and searching power of X-rays.

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Iron Ore Developments in Sierra Leone.

By WODEHOUSE S. EDWARDS, M.I.Mech.E.,
Fraser & Chalmers Engineering Works of the G.E.C.

INTRODUCTION.

THE iron mine of the Sierra Leone Development Co., Ltd. is situated at an altitude of approximately 300 feet above sea level, and is connected with the sea-board by a single-line railway 50 miles in length, which the Company had to build.

The vast extent of the scheme for preparing, handling and shipping the ore will be appreciated by a consideration of the scope of the contracts which were entrusted to Fraser & Chalmers Engineering Works. These included, at the mine, complete washing, screening and loading plant for the washed ore, conveying and storage equipment for the washed fines, conveying and storage machinery for the concentrates, and a large proportion of the special machinery required for the concentration plant.

For the installation at the port, the work undertaken included the storage and rehandling plant for the washed fines and concentrates. In addition the whole of the motors, switchgear, sequence control and distribution equipment was designed and manufactured at Witton Engineering Works.

As a result of long continued pioneering on the part of the Sierra Leone Development Co. Ltd., with the object of exploiting the iron resources of the colony, so much progress had been made by 1933, that a first cargo of iron was shipped to Glasgow.

Rapid development followed and facilities for washing and screening the ore became necessary; also handling, storage, and loading plant for dealing with the washed fines and concentrates were required both at the mine and the port. In order that the most efficient types of equipment should be installed for these purposes, Fraser & Chalmers Engineering Works was requested to undertake extensive experiments, and this led eventually to the placing of contracts for the large and comprehensive plants which it is the purpose of this article to describe.

ORE HANDLING AT THE MINE.

Washing and Screening.

The ore is brought to the plant in mine tubs and discharged by the mine tipplers into conical hoppers; they, in turn, discharge on to the shaker feeders, each of which delivers to a double-deck Robins Gyrex screen, 60ins. by 120ins. The screens are equipped with a suitable water service which thoroughly washes the material as it passes over. The oversize is fed on to a 24-inch belt conveyor which inclines upwards and discharges the washed product into a 400-ton steel bunker equipped with discharge gates and operating gear for loading the 30-ton steel railway wagons in which the ore is transported to the port, a distance of 50 miles, where it is handled by an existing ship loading plant.

The fines from the screen are conveyed by means of flumes and sluices to a Dorr classifying plant and for a time the recovered material was allowed to accumulate in the vicinity. During 1937, however, it became evident that some means would have to be provided for dealing with the large accumulation of washed fines for which, by then, a market was available. A scheme was therefore developed and orders placed for an extensive handling and storing plant.

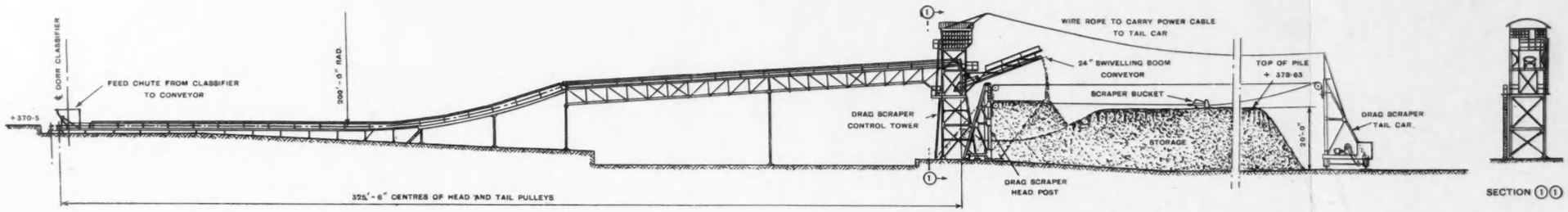
Storage.

To prevent the discharge from the classifiers collecting in the immediate neighbourhood, a 24-inch belt conveyor, over 300 feet long, has been installed, which terminates in a short boom conveyor capable of being swung through a considerable arc and enabling a large initial pile of material to be accumulated. From this point the material is distributed by a Sauerman drag line scraper over a large semi-circular site of 300 feet radius with a storage capacity of 250,000 tons. The haulage winch, which is adjacent to the pile, is driven by a 150 h.p. motor, remote controlled from the elevated operating cabin at the top of the tower.

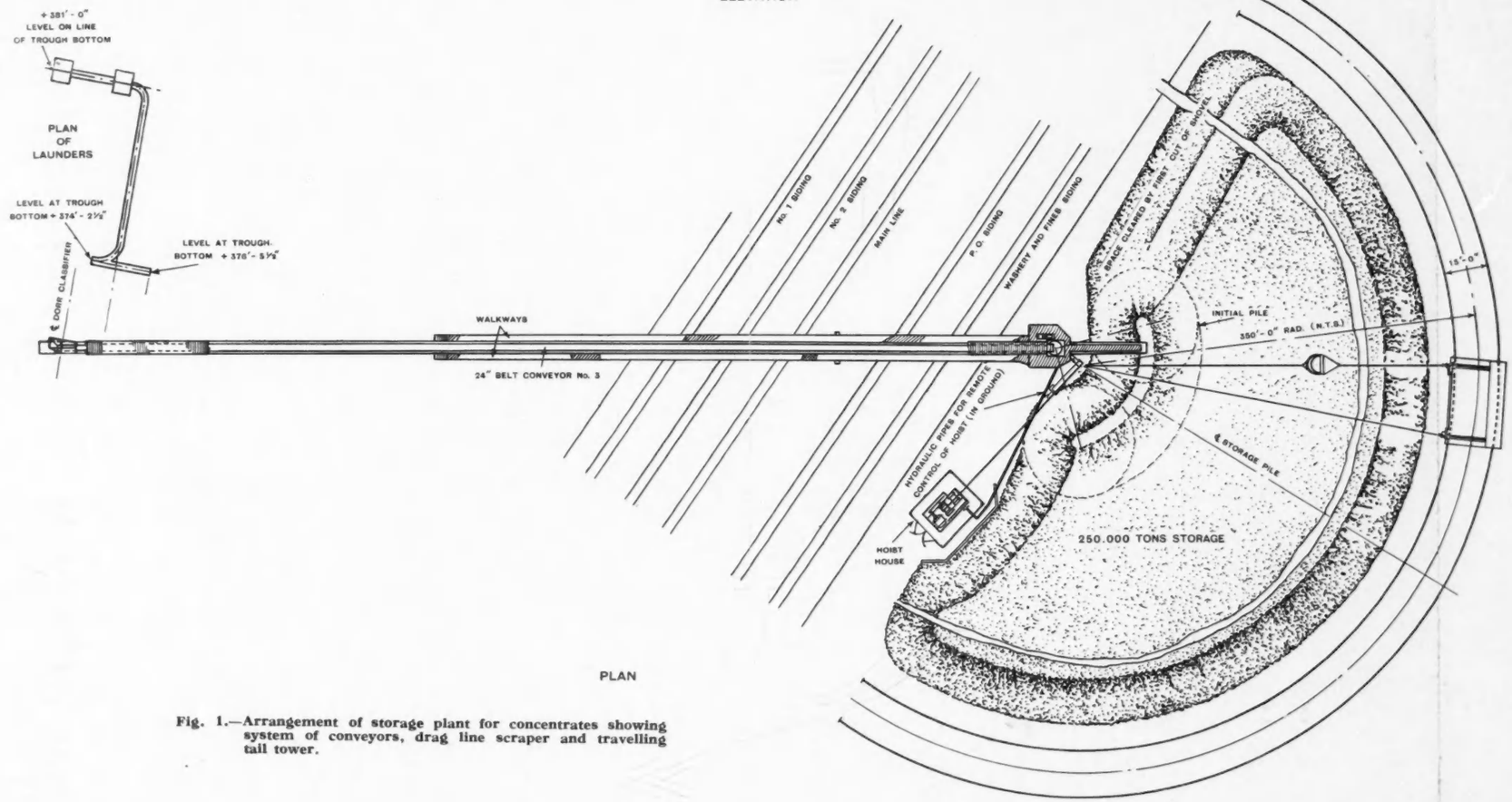
The tail tower travels on a semi-circular track of 15 feet gauge, and can be moved in either direction; it also is under remote control from the driver's cabin. The material is discharged on to the pile at the rate of 200 tons per hour. It should be mentioned that the drag line scraper serves only to put the material into storage, whence it is recovered and loaded into standard 30-ton railway wagons by means of an electrically operated mechanical shovel. The general arrangement is shown in fig. 1.

Concentration and Storage of Micaceous Iron Ore.

The company opened up also a large deposit of soft, powdery micaceous iron ore mostly under 1/16 in. in size. An extensive concentrating plant was designed and built at the mine for which a battery of Sherwen electric vibrating screens was supplied, a typical example of this type of screen being shown in fig. 2. Suitable handling and storage plant became necessary for dealing with the output of this



ELEVATION



PLAN

Fig. 1.—Arrangement of storage plant for concentrates showing system of conveyors, drag line scraper and travelling tail tower.

plant and during 1937 a further plant was developed and built for this purpose by Fraser & Chalmers Engineering Works.

The method of handling this particular material called for special consideration by reason of the fact that, even when dry, the concentrates flow very readily and behave almost like fine sand, while when moist the material has no angle of repose at all and flows over the ground like a liquid. It was suggested that for its storage an overhead conveyor should first be constructed to build a dump from beneath which a second conveyor, running in a tunnel, could recover the material through suitable gates. As a result of experiments carried out with some tons of the material, specially sent over for the purpose from West Africa, the final arrangement depicted in figs. 3 and 4 was adopted and has proved highly successful.

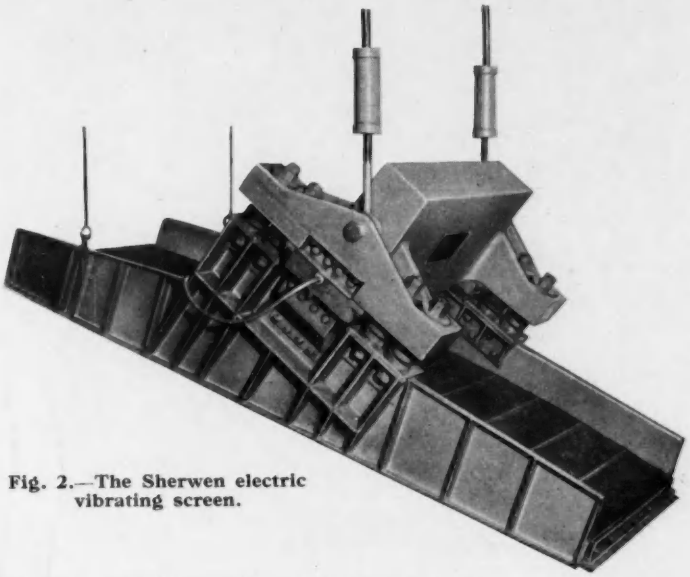


Fig. 2.—The Sherwen electric vibrating screen.

This consists of a long 24-inch inclined conveyor leading from the concentrating plant to an overhead conveyor with a travelling tripper by means of which a pile of 20,000 tons of concentrates can be accumulated. The moisture is then allowed to drain off the stored concentrates and the material is recovered by means of the electrically operated excavator which loads it into railway wagons, fig. 4, for transportation to the port.

ORE HANDLING AT THE PORT.

Port Facilities.

The next problem which had to be solved was the provision of the necessary facilities for unloading the wagons at the port and the arrangement of suitable bulk storage of sufficient capacity to enable ships coming alongside to be fully loaded with the minimum of delay. The plant finally evolved, which has since been built and put into operation, is shown in figs. 5, 6, 7 and 12.

Fig. 4.—Electric shovel reclaiming powder ore and loading it into railway wagons for transportation to the port.

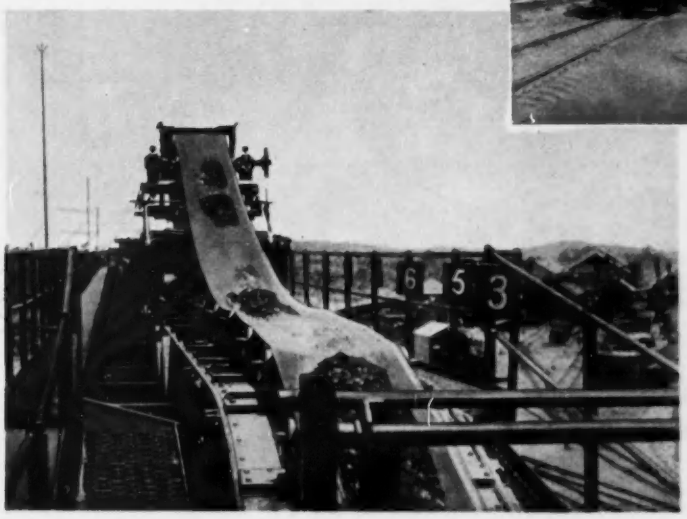


Fig. 3.—Travelling tripper discharging powder ore on to the storage heap.

On arrival at the port the 30-ton wagons of concentrates and washed fines are unloaded by a Marshall car tippler which is designed to work on a 3-minute cycle of operation enabling 20 wagons or 600 tons of material an hour to be emptied.

Car Tippler.

The car tippler consists of four main parts :—

(1) A rail frame, or table, upon which the wagon is placed ;
(2) A pair of lifting arms attached at their upper ends to a steel trunnion to the side of which is attached the lower bolster ;
(3) A pair of rolling arms complete with rolling path and upper bolster ; and
(4) A superstructure built above the machine for supporting the hoisting drums, motor and gearing.

In its normal position the rail frame rests upon solid foundations so that the tippler and ropes are not stressed by through traffic. The loaded wagon to be discharged is run on to the rail frame and the brakes applied. The electric hoisting gear is then put into action. Immediately the lifting arms begin to rise, the rail frame with the wagon is gradually inclined towards the bin until the side of the wagon comes into contact with the lower bolster. The wagon, frame and lifting arms now constitute a single unit revolving about the trunnion pins. When the top of the wagon meets the upper bolster attached to the rolling arms a final unit is formed which subsequently revolves and rolls along the rolling path until the load is fully discharged. The hoisting gear is then reversed and the wagon returned to its original position in readiness for removal.

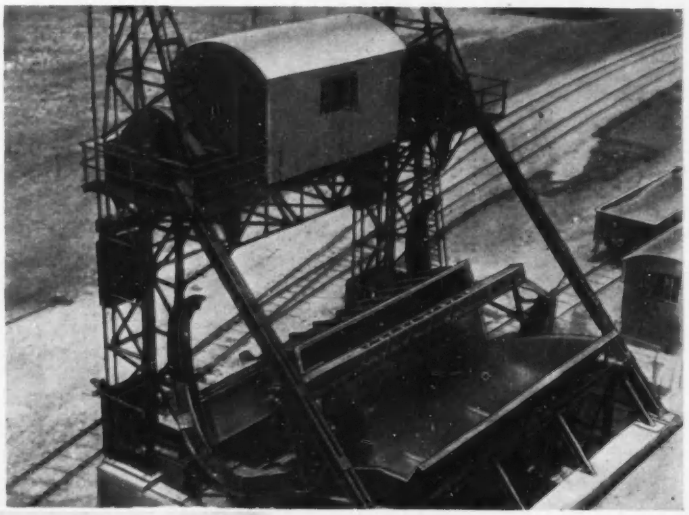


Fig. 6.—Near view of the Marshall car tippler unloading a 40-ton railway wagon.

Fig. 5.—General view of the Marshall car tippler equipment.

The two winches are driven from one motor through suitable gears and shafting. The hoisting gear is electrically operated by means of a 45 h.p. slipring induction motor controlled by a push-button from an automatic contactor panel situated adjacent

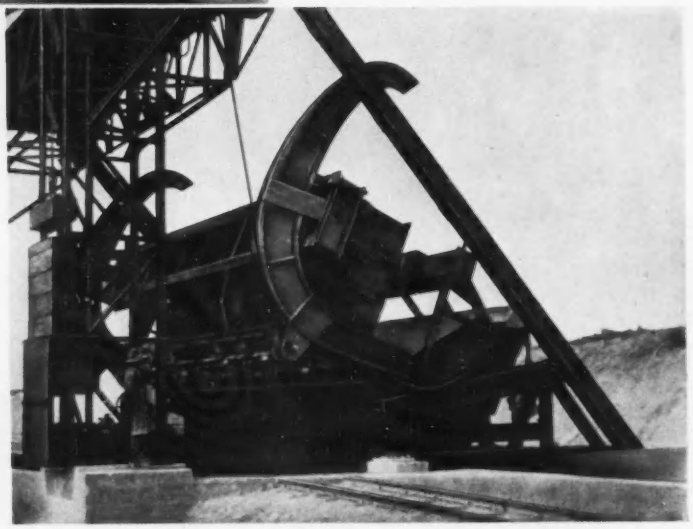


Fig. 7.—The Marshall car tippler with the truck raised and about to discharge into the conveyor hoppers.

to the machine. To prevent overwinding or failure on the part of the operator to stop the machine when the tipping position is reached, an automatic cut-out

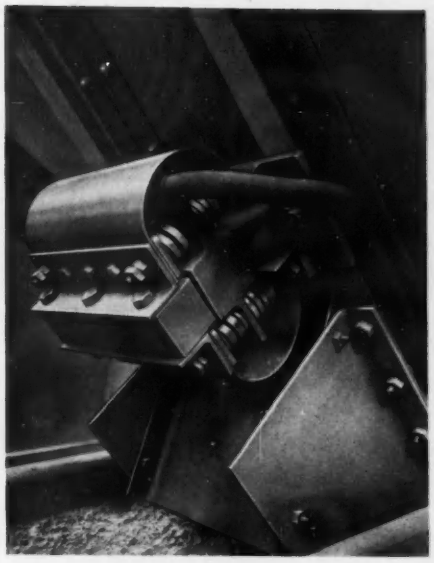


Fig. 8.—The Sherwen vibrator attached to the side of the steel hopper.

is provided. At the bottom of the wind a similar device is fitted to stop lowering automatically when the tippler is at rest on the foundations.

Sherwen Vibrating Equipment.

In order to deal with the fine ore when in a sticky condition a Sherwen vibrating equipment, fig. 8, is fitted both on the tippler and on the sides of the hoppers beneath it.

The principle of operation is extremely simple: the vibrating mechanism consisting of two former-wound coils connected in series with a half-wave metal rectifier and a moving armature mounted on a cantilever steel spring and connected by coil springs to the tippler or hopper. During the first half of the A.C. cycle the armature and the object to which it is connected are drawn forward against the pressure of the spring while, during the second half, the rectifier prevents the passage of any current, thus enabling the springs to accomplish the return stroke. Therefore with an A.C. supply at 50 cycles the frequency of vibration is 3,000 strokes a minute. Provision is also made for varying the amplitude of vibration. It may be added that the apparatus has proved most successful in clearing wagons and similar vessels of sticky materials which hitherto had to be scraped out by hand. The apparatus maintains a steady flow of material without in any way damaging the hoppers and can conveniently be adapted for remote control so as to be brought into operation from a distance either automatically or by hand.

Conveyor System.

After leaving the tippler the concentrates and the washed fines are fed to the 30-inch conveyor belt No. 1 by means of three Sherwen vibrating feeders, fig. 9. Rheostat control is provided giving instantaneous variation of the speed at which the material travels along the feeder. It is thus possible to vary the tonnage delivered by the feeder, in very small steps, from zero to the maximum for which the machine is designed.

From belt No. 1 the material is fed by a travelling tripper on to the inclined conveyor No. 2 which raises it to the level of belt No. 3 on a travelling bridge, figs. 10, 11 and 13, by means of which either kind of material can be stored over a large area, the normal capacity being approximately 22,000 tons of each. The ore is recovered by two 4½-cubic yard Sauerman drag line crescent scrapers, each attached to a travelling tail car, and each operated by a 300 h.p. electric winch. This method of storing and reclaiming is seen in fig. 14. The driver's cabin (partly seen to the right of fig. 10) from which both the winches and tail cars are remote controlled, is situated at such a height as to command a good view of the whole of the storage ground. The material thus recovered by the drag line scraper equipment is fed by means of a circular hopper on to a belt

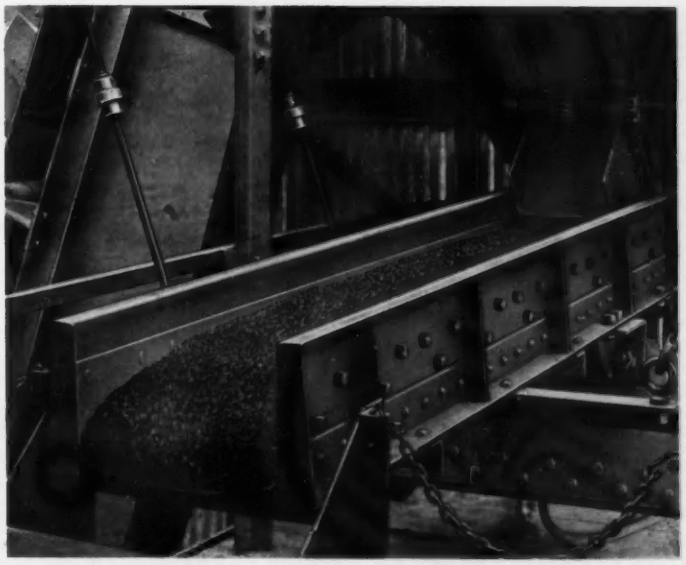


Fig. 9.—The Sherwen electric vibrating feeder. Three of these feeders are used for drawing off the washed fines or powder ore from under the conveyor hoppers and loading the material on to the belt.

feeder which, in turn, delivers it to the end of the 42-inch belt No. 4. Towards the end of this conveyor the ground falls away so that the conveyor is inclined downwards at a slight angle. No. 4 conveyor delivers the material on to the end of an existing loading conveyor.

The control tower is provided with two powerful searchlights which can be moved in any desired direction by the operator. On top of the tail towers there is a powerful electric horn in order to give warning when either of them is going to be moved, and also to caution the workmen that the trolley wires round the site are alive.

Fig. 11.—Inclined conveyor feeding the storage bridge.

ELECTRICAL EQUIPMENT.

The details of the electric drives of the plant at the port are given in a table on page 101.

Distribution Boards.

The main switchboard is built up of ironclad industrial draw-out type oil circuit breakers, comprising nine units in all, and receives an A.C. supply from the power station at 500 volts 3 phase 50 cycles, which is distributed to the various conveyor motors, drag scraper motors and to the lighting transformers. The bridge control board consists of four ironclad oil circuit breakers and is supplied through three-phase collectors and trolley wires from a feeder on the main board, while two additional sets of trolley wires supply each of the tail towers individually. The traverse motors for the tail towers are high torque squirrel cage machines, the drum controllers for which are mounted in the centre control tower enabling the operators of the drag scrapers to move the tail towers as they may require. The bridge is traversed by means of two 12½ h.p. slipring induction motors, one at each end, controlled by a common drum controller and synchronised by an arrangement of resistances in the rotor circuits. This ensures that each motor makes the same number of revolutions so that both ends of the bridge move by the same amount. Solenoid operated brakes and rail clamps serve to secure the bridge when at rest.

Fig. 10.—Travelling storage bridge and dump at the port.

Sequence Operation of Conveyor System.

The whole of the conveyor system is electrically interlocked so that all the conveyors, including those on the bridge, must be started up in the correct sequence. This ensures that no running conveyor can feed on to a standing conveyor and that if any conveyor shuts down those feeding

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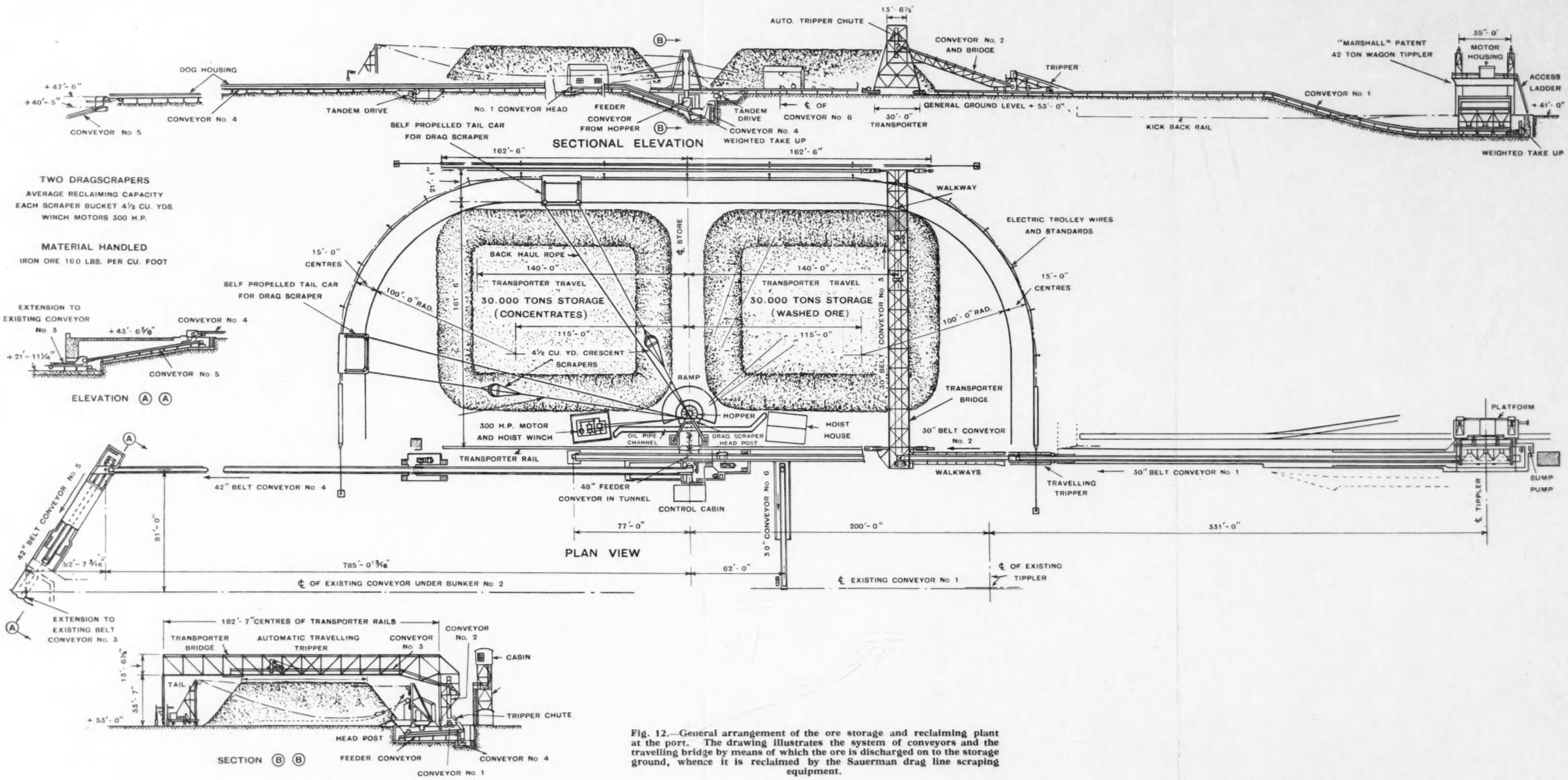


Fig. 12.—General arrangement of the ore storage and reclaiming plant at the port. The drawing illustrates the system of conveyors and the travelling bridge by means of which the ore is discharged on to the storage ground, whence it is reclaimed by the Sauerman drag line scraping equipment.

on to it are automatically brought to rest. The interlocking system has, however, to provide for various alternative sequences, accordingly tappet switches, in operation. By means of changeover switches arrangements are also made so to connect the interlocking circuits as to provide for the alternative

Fig. 13.—Head of the inclined conveyor, showing the even distribution of ore on the belt.

operated according to the mechanical relation of the bridge to the various conveyors, correctly connect the sequence wires for the actual sequence methods of working. A fourth trolley wire is supplied to connect the interlocking circuits to the conveyors on the travelling bridge.

MOTORS AND STARTERS.

Equipment Driven	No. of Motors	Type of Motor	H.P.	Speed	Voltage	Method of Drive	Type of Starter
No. 1 Drag Scraper	1	Slipring	300	585	550	Chain and spur	Liquid starter
No. 2 Drag Scraper	1	Slipring	300	585	550	Chain and spur	Liquid starter
Conveyor No. 1	1	Slipring	65	730	550	Worm gear	Oil immersed rotor starter
Conveyor No. 2	1	Slipring	25	730	550	Worm gear	Contactor control
Conveyor No. 3	1	Slipring	25	730	550	Worm gear	Oil immersed rotor resistance
Conveyor No. 4	1	Slipring	130	735	550	Worm gear	Oil immersed rotor resistance
Conveyor No. 5	1	Driven from Conveyor No. 4			—	—	—
Conveyor No. 6	1	Slipring	15	725	550	Worm gear	Contactor control
Feeder Conveyor	1	Slipring	35	725	550	Worm gear	Oil immersed rotor starter
Traverse Motors	2	Slipring	12½	600/750	550	Worm and spur	Rotor resistance synchronising gear
Drag scraper Tail Tower No. 1	1	Squirrel Cage	24	765	550	Worm and spur	Reversing drum switch
Ditto. No. 2	1	Squirrel Cage	24	765	550	Worm and spur	Reversing drum switch
Sump Pump	2	Squirrel Cage	2½	720	550	Texrope	Direct to line starter
Wagon Tippler	1	Slipring	45	725	550	Worm and spur	Automatic contactor panel

Tippler and Drag Scraper Control.

The tippler room distribution board, which is fed directly from the power station, comprises four ironclad oil circuit breakers and controls the wagon tippler motor, the Sherwen feeders, the vibrators for the tippler and feeder conveyors, and the sump pump motor.

The 300 h.p. slipring motors driving Nos. 1 and 2 drag scrapers and the 130 h.p. slipring motor for No. 4 conveyor are each individually controlled from an ironclad industrial draw-out type circuit breaker.

In all cases where the conveyor motors are adjacent to the switchboards, hand operated rotor starters are provided but where the motors are situated at a distance remote operated contactor starting is employed.

Fig. 14.—The drag line scraper reclaiming ore from the heap.

In conclusion, the author would express his indebtedness to The Sierra Leone Development Company for their ready assistance in providing photographs and information, and for their kind permission to publish a description of this important plant.

The High Rupturing Capacity Cartridge Fuse.

WITH SPECIAL REFERENCE TO SHORT-CIRCUIT PERFORMANCE

PART I.*

By J. W. GIBSON, M.Eng., A.M.I.E.E.,
Development Department, Witton Engineering Works.

After a summary of the advantages of the high-rupturing-capacity cartridge fuse, the breaking-capacity requirements for fuses for use in low- and medium-voltage circuits, as set forth in British Standard Specification No. 88—1939, are enumerated. The short-circuit operation of cartridge fuses is discussed, at first in a general way and then in the light of detailed investigations of the phenomena during the melting and arcing periods. Conclusions are drawn, both analytically and from test results, as to the effect of circuit conditions on the duty imposed, and these are compared with the requirements of British Standard Specification No. 88.

Following a section dealing with the choice of materials, the various types of fuse for low- and medium-voltage circuits and for high-voltage circuits are considered. The article concludes with notes on the application of these fuses.

This paper was read before the Institution of Electrical Engineers in April, 1940.

(1) INTRODUCTION: REQUIREMENTS AND ADVANTAGES.

THE progressive increase in the short-circuit capacity of distributing networks, both at high and medium voltages, has emphasized the necessity of using fusegear of high breaking capabilities and proved performance. This necessity has made itself felt not only in such obvious cases as cable networks, power house auxiliaries, large-scale industrial distribution and so on, but also in the case of rural and domestic supplies. The demand has been satisfactorily met by fuses of a number of types, of which the one which has the largest field of use and is applicable to the widest range of voltages is the filled cartridge fuse forming the subject of the present paper. This fuse in its more advanced forms is a reliable piece of apparatus with a precision performance. In essence, it consists of a fuse-element surrounded by an arc-extinguishing filler in the form of a granular non-conducting material, the whole being totally enclosed in a tubular insulating container; the special capabilities of the fuse arise largely from the control of the arc by a solid, instead of a gaseous or liquid, extinguishing agent.

High-rupturing-capacity (H.R.C.) cartridge fuses are now made with breaking capacities such as to permit their use on high-power systems, typical values (3-phase) being 25 MVA at 440 volts, and 300 MVA at 33 kV. The rapid increase in their use has come about partly because of their high short-circuit performance but also because of other advantages, which often indicate their use in place of older designs of fuses and circuit-breakers. The advantages may be summarized as :—

(*a*) High breaking capacity.

(*b*) Absence of deterioration.

(*c*) Consistent calibration, leading to—

(*d*) Reliable discrimination with circuit-breakers or other fuses.

(*e*) Cool running.

(*f*) Absence of noise and external flame. The resultant reduction in the necessary clearances, as compared with semi-enclosed fuses, may lead to a reduction in the sizes of fuse boxes and the like.

(*g*) High speed of operation on short-circuit

(*h*) Marked current-restricting effect with heavy prospective currents, greatly reducing the deleterious effects of short-circuits. It may be noted that this effect is similar to that obtained by the use of D.C. high-speed circuit-breakers, but is usually even more pronounced.

(*i*) Low value of voltage peak, whether operating on overload or on short-circuit, reducing the possibility of flash-over of, or cumulative damage to, system insulation.

(*j*) Inverse time/current characteristic is inherent, even up to very large currents.

* NOTE.—The numerical references in the text are to the Bibliography which, together with the Appendices, will be published with Part II of this article.

(*k*) Low cost.

Perhaps the greatest difficulty in the development of these fuses has been that the cost of development testing is extremely high in comparison with the price of the article; each design requires extensive full-power breaking tests, often both A.C. and D.C.*

(2) BRITISH STANDARD SPECIFICATIONS FOR FUSES.

There are at present three British Standards for fuses, viz. No. 88—1939,[23] No. 646—1935[9] and No. 714—1936[11], none of which applies to voltages above the low and medium ranges. Since the second and third do not specify breaking capacities above 500 amperes, they will not be considered further.

The principal items covered by British Standard Specification No. 88 are: (1) current ratings; (2) temperature rise; (3) fusing factor†, and (4) duty, *i.e.*, breaking capacity. A number of the points enumerated in the preceding section are not considered, though (*a*) and (*e*) are covered. It has not so far proved practicable to standardize dimensions.

The clause dealing with duty standardizes four values of breaking capacity expressed in terms of current, *viz.* 1,000, 4,000, 16,500 and 33,000 amperes, representing all classes of duty from light domestic to heavy industrial. Because of the current-restricting effect of fuses, short-circuit values are expressed, not as the current which flows through a fuse on test, but as a prospective current, meaning the current which would flow if the fuse were replaced by a link of negligible impedance.

Test voltages are given as 250 for direct current and 250 or 440 for alternating current, and are such as to take account of the variation of voltage conditions with the type of circuit. Thus in the case of a D.C. 3-wire system a short-circuit between one outer and the mid-wire is interrupted by one fuse, but a short-circuit between outers will find two fuses in series; it is therefore proper that proving tests

* See Appendix 5.

† Fusing factor is defined as "the ratio, greater than unity, of the minimum fusing-current to the current-rating."

LIST OF SYMBOLS.

I_s = prospective current (D.C.) or R.M.S. symmetrical prospective current (A.C.).
I_{tp} = instantaneous value of current during pre-arcing period.
I_{ta} = instantaneous value of current during arcing period.
I_{ts} = instantaneous value of prospective current.
I_f = cut-off current.
I_c = minimum fusing current.
$i = I_{tp}/A$ = instantaneous value of current density during pre-arcing period.
i_0 = prospective current density (D.C.) or symmetrical peak value of prospective current density (A.C.)
B = rate of rise of current in quick-acting fuse during pre-arcing period.
θ = temperature of fuse element, ambient temperature as datum.
θ' = apparent temperature of fuse element, ambient temperature as datum.
θ_m = melting temperature, ambient temperature as datum.
θ_v = vaporization temperature, ambient temperature as datum.
$\Delta\theta$ = temperature rise above melting point.
c = specific heat, in joules per cm^3
h = latent heat of fusion, in joules per cm^3
$v_w = lA$ = volume of fuse element.
$v = lA_2$ = volume of melted part of fuse element.
R = resistance of circuit.
R_f = resistance of fuse element.
R_1 = resistance of fuse element at start of melting.
t = time.
t_p = pre-arcing time.
$T = L/R$ = time-constant.
L = inductance.
C = total current/heat integral.
l = length of fuse element.
A = cross-sectional area of fuse element.
A_1 = cross-sectional area of solid part of fuse element during melting.
A_2 = cross-sectional area of liquid part of fuse element during melting.
d = diameter of fuse element.
ρ = resistivity.
ρ_0 = resistivity at ambient temperature.
ρ_1 = resistivity (solid) at melting temperature.
ρ_2 = resistivity (liquid) at melting temperature.
ρ_m = harmonic mean of solid and liquid resistivities at melting temperature.
α = temperature coefficient of resistance (solid), ambient temperature as datum.
β = temperature coefficient of resistance (liquid), melting point as datum.
E = circuit e.m.f. (D.C.) or peak value of circuit e.m.f. (A.C.).
V_a = arc voltage of fuse.
k = Preece's coefficient.
W = peak value of inductive energy.

should be made on single fuses at the maximum voltage normally imposed between an outer and the mid-wire, *viz.*, 250 volts. Similar considerations fix the test pressure for single-phase and 2-phase alternating current at 250 volts. In the case of a 3-phase circuit with 440 volts between the lines it is common for only two of the three fuses to be blown on a 3-phase short-circuit between phases, so that these two both have to clear against the full phase-to-phase voltage.[15] Tests at 250 volts are therefore specified for fuses for use on direct current (whether between an outer of a 3-wire system and neutral or between outers) at the usual voltages and on single-phase alternating current; and 440-volt tests are specified for fuses for use on 3-phase systems of the usual voltages. It may also be noted that in the 3-phase case the test voltage for circuit-breaker tests made single-phase is $1{\cdot}5/\sqrt{3}$ of the line voltage;[20] the difference arises because in the case of a circuit-breaker all three phases assist in clearance of the short-circuit. Category 440AC4 of British Standard Specification No. 88 corresponds to a 3-phase short-circuit kVA value of $\sqrt{3} \times 0{\cdot}44 \times 33{,}000$, equal to 25,000, which is about the maximum value that can be considered to be good practice in general distribution work. Short-circuit power factors for the different A.C. categories have been chosen as representing the values likely to be associated in distribution networks with the corresponding short-circuit currents. In an analogous way the inductances of D.C. systems have been taken into account by specifying values for the ratio of inductance to resistance, *i.e.*, the time-constant.

It will thus be seen that the test conditions bear a logical relation to the circuits in which the fuses are to be used. The relation between the test conditions and the severity of the test is a different matter, and this is discussed later.

While the semi-enclosed (re-wirable porcelain) fuse is usually suitable for no higher category than 440AC2, corresponding to 3 MVA, 3-phase, a well-designed cartridge fuse will easily deal with the 440AC4 conditions, which correspond to 25 MVA 3-phase.

(3) GENERAL PRINCIPLES OF OPERATION AND DESIGN.

While the factors determining severity in circuit-breaker operation have been the subject of intensive study and research, it seems clear that this work is of only limited application in connection with fuses, and particularly cartridge fuses, the action of which in interrupting a circuit will be shown to be very different from that of circuit-breakers.

A suitable solid fuse-filler has a higher arc-extinguishing power not only than air, but also than oil, owing to its property of readily absorbing and cooling metallic vapour from the arc. Most of the vapour is condensed at points remote from the arc, though some enters into chemical combination with the filler. The resultant hot column of filler and vapour sets up a high, stable, and consistent arc voltage, which in practice may be as high as 1,000 volts per inch or more. This high value is dependent partly on the effect of pressure set up by the metallic vapour itself (though it may be mentioned that far higher pressures are set up in an *unfilled* cartridge). Many designs therefore employ complete enclosure and high mechanical strength to allow this high

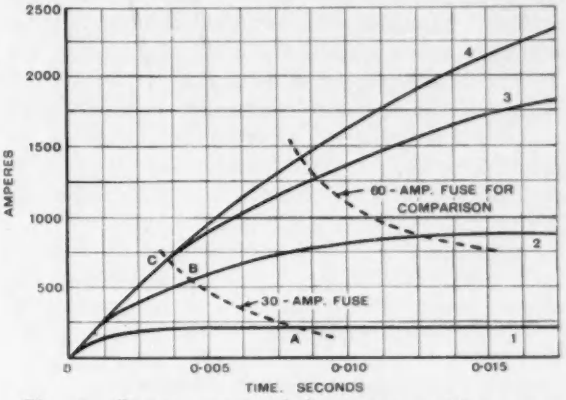


Fig. 1.—Curves, prepared from test oscillograms, illustrating saturation effect in D.C. circuits.

pressure to build up and to be resisted. Others, mentioned later, provide a deliberate release for the pressure.

The effect of the arc voltage in reducing the current to zero may be visualized as the introduction of a steadily increasing resistance in the current path. The function of the usual oil or air circuit-breaker operating on alternating current is to prevent re-establishment of the arc when it is momentarily extinguished as a result of the current passing through zero, either on the first or on a subsequent occasion. In the meantime this voltage drop in the arc is, in general, small compared with the system voltage, so that the arc has little direct effect in reducing the current, which in a circuit of low power factor will continue to lag by nearly 90°. A similar action takes place in many fuses; for example, all high-voltage fuses except the filled cartridge fuse appear to operate in this way. On the other hand, the cartridge fuse, whether for low voltage or high voltage, immediately on vaporization of the element develops an arc voltage that is usually high enough to initiate an immediate reduction of current, at whatever point in the voltage wave the arc may commence. At the same time the effect of a sudden introduction of high resistance is to advance the phase of the current, and, if the arcing period is as long as about $\frac{1}{4}$ cycle, the current by the time extinction takes place will have been forced approximately into phase with the voltage. Since the action

does not depend on the natural passage of the short-circuit current through zero, the fuse has a similar performance with direct current as with alternating current. This is in contradistinction to other types of circuit-breaking apparatus, which have a much lower breaking capacity with direct current.

The filler has the second property of being able to abstract a large amount of energy from the circuit. For example, a filler of silica, used in conjunction with a silver fuse-element, can absorb approximately 2 kW-sec. per gramme. The greater part of the energy absorbed is used in fusing together the grains of filler surrounding the arc, the resulting fulgurite remaining as a witness to the action of the arc.

The smaller the cross-section of the element the easier will be the duty of the fuse, since the arc contains less metallic vapour to be cooled by the filler. This is an invariable and a cardinal point in the design of cartridge fuses. It may be noted that in other types of fuse, particularly those depending for arc extinction on a gaseous blast effect generated by the arc itself, a large quantity of metal in the element may, within certain limits be advantageous, by strengthening the blast.

Methods of obtaining a Reduced Cross-section.

The very important reduction of cross-section may be obtained in a number of ways, and modern designs usually employ a combination of these, which are as follows :—

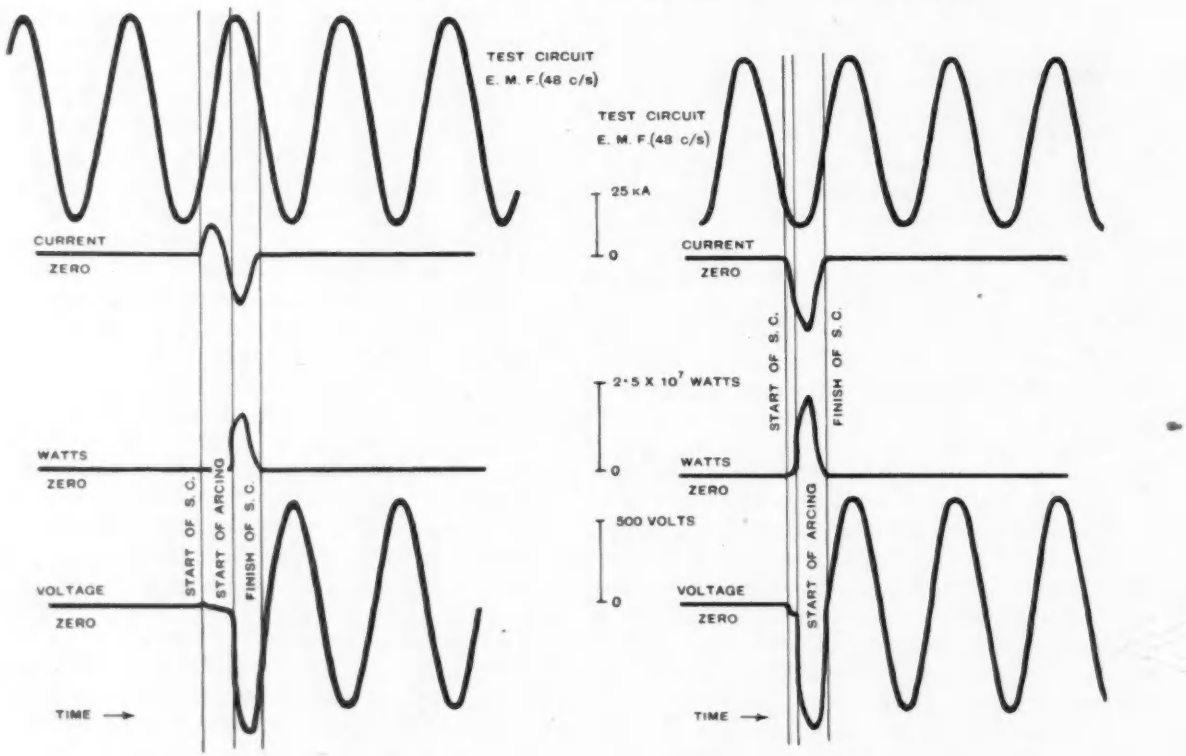
(*a*) Low fusing factor. Fusing factor is, however, largely determined by other considerations, such as the extent to which overload protection is required.

(*b*) The use of a metal of high electrical conductivity and high melting-point, resulting in a high value of Preece's coefficient.*

(*c*) Increased dissipation of heat from the element, resulting in the use of a smaller section for a given fusing current. This is inherent in the filled cartridge fuse, because the relatively high thermal conductivity of the filler results in greater dissipation than from a wire surrounded by air, the corresponding increase in fusing current being usually about 2·9 times. Application of Preece's Law shows that, for a given value of fusing current, the cross-section is reduced in the ratio $1/2 \cdot 9^{4/3}$, *i.e.*, to rather less than a quarter.

(*d*) Subdivision into a number of parallel elements, securing a very appreciable reduction of the total section, on account of the increased surface for dissipation. The reduction is, however, not quite as great as if the parallel elements were in separate cartridges, for which case it may easily be shown from Preece's Law that the total section of the parallel elements for a given fusing current is

* Preece's Law states that fusing current $I_F = kd^{3/2}$, k being called Preece's coefficient [see Section (7) of the paper and Bibliography (1)].



(*a*) Short-circuit initiated on falling voltage. (*b*) Short-circuit initiated on rising voltage.

Fig. 2.—Category 440AC4 : tests on 400-amp. fuse.

inversely proportional to the cube root of the number of elements. It may be pointed out that subdivision also results in a stronger extinguishing effect, through a greater area being exposed to the action of the filler, causing a higher arc voltage where the section of element is small.

(*e*) Increased conduction of heat along the element, which has on the cross-section required an effect similar to that of conduction through the filler. The fuses covered by British Standard Specification No. 88 are sufficiently short for the end caps or terminals to have an appreciable effect in the direction desired. In addition many designs, instead of using an element of the same section throughout its length, employ one having one or more parts (to be called "necks") of reduced section, the heating of which determines the fusing current. Conduction along the element away from the neck thus reduces the cross-section required.

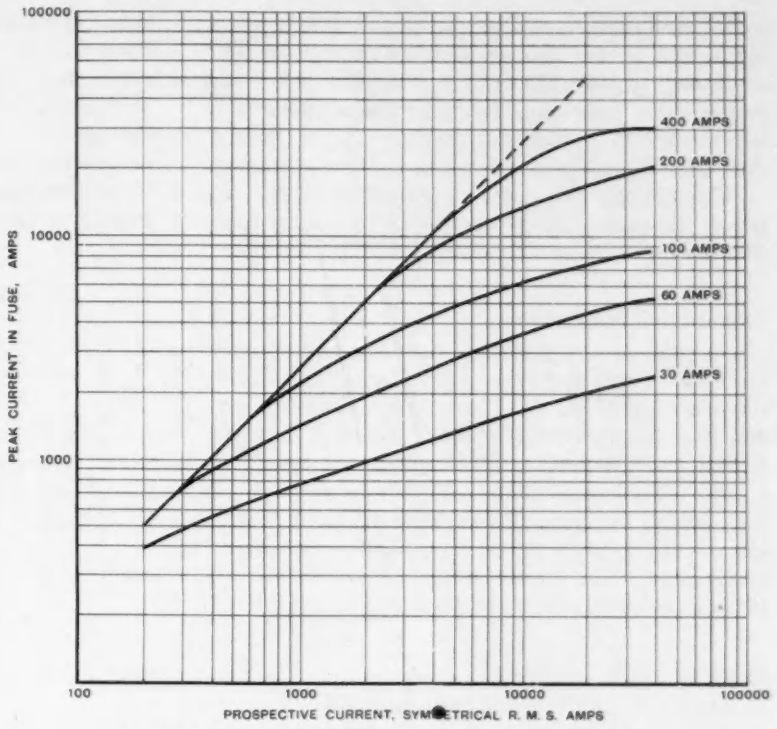


Fig. 3.—Current-restriction curves for cartridge fuses of various sizes. Frequency 50 c./s.

A small section of element also results in a very valuable current-restricting effect. This effect arises because the smaller the section of the element of a fuse subjected to short-circuit, the more quickly does fusion take place. If the prospective current is high and the thermal capacity of the element low, fusion takes place before the full prospective current of the circuit is reached, so that both the current at which arcing commences and the pre-arcing time are low. Further, the energy to be dealt with by the fuse in the subsequent arcing period is reduced. Thus, if a reduced short-circuit current results from the use of a small cross-section, an easement of the breaking duty (equivalent to an increase in breaking capacity) is obtained in addition to that resulting from the reduction in the quantity of metal to be de-ionized. It has long been realized* that current-restriction is a factor of great importance in the design and application of fuses. A cartridge fuse of low current rating, and so of small physical dimensions, can conveniently be made to have a breaking capacity similar to that of a much larger fuse of the same type of design ; this valuable feature is a result of the greater current-restricting effect of the small fuse. Current-restriction is investigated in the next section.

(4) INVESTIGATION OF PRE-ARCING CONDITIONS. Mechanism of Fusion.

A fuse will first be considered in which a D.C. short-circuit current rises instantaneously to a steady value. The justifiable assumption is made that the pre-arcing period is sufficiently short for dissipation of heat by the element to be negligible, so that, except for variations of initial temperature, the energy to be supplied during the period is constant for any particular fuse. Since for pure metals the resistance increases very considerably with temperature, while the specific heat does not vary greatly, it follows that the temperature rises at an increasing rate until the melting point is reached. It then remains steady while the power developed by the current is devoted to supplying the latent heat of fusion, after which it increases at a rate which is further augmented by reason of the increase in resistance which occurs when the metal changes from the solid to the liquid state. A pinch effect may intervene[12] to initiate arcing while the bulk of the metal is still liquid, but this is less likely to occur[16] under short-circuit conditions when the heating is extremely rapid. Even if the liquid column remains intact until vaporization commences, a number of factors then intervene to disperse it and initiate arcing. On account of the progressive increase in power loss, caused by the increase in resistance with temperature, these latter stages are passed very quickly with a resultant considerable reduction in the pre-arcing time. For example, for silver† nearly 75% of the pre-arcing period occurs before the com-

* Oelschläger, quoted by Schwartz and James [see Bibliography (2)].

† See Appendix 1.

mencement of fusion, though the proportion is less for metals of low melting point, such as tin. The conditions are modified if, during the pre-arcing period, the resistance of the fuse reaches a value able appreciably to reduce the current, but in general this effect is small and will not be considered further.

Calculations are given in Appendix 1 for the input, expressed in terms of current and time, necessary to initiate arcing with different metals.

Effect of Circuit Constants.

In practice the presence of inductance prevents an instantaneous rise of current. For the short times considered, changes in system inductance, resistance and electromotive force may be ignored. The well-known result is that in a D.C. circuit the pre-arcing current rises exponentially while in an A.C. circuit supplied by a sinusoidal voltage it consists of an A.C. sinusoidal component and a D.C. exponential component. The factors which determine whether current restriction takes place will now be considered.

Operation on Direct Current.

Direct current will first be considered in the light of oscillograph tests on a certain 30-ampere cartridge fuse. With a particular value of non-inductive resistance added to the circuit the growth of current follows the exponential curve shown at 1 in fig. 1, the initial slope of which is simply the quotient of voltage by inductance, being independent of resistance. The fuse is found to melt at the point A. If now, the voltage and inductance remaining unchanged, the resistance is reduced, curve 2 results and fusion takes place at B. Further reduction of resistance results in curve 3 and fusion at point C on the initial substantially straight part of the curve. A further reduction of resistance to give curve 4 results in fusion still taking place at C, since the curves 3 and 4 follow substantially the same course until after point C. Thus increase in prospective current beyond a certain limit does not result in an increased cut-off current to be handled by the fuse. This limiting current has been termed[22] the "saturation current" of the fuse, but it should be noted that it is not an absolute property of the fuse, as it depends also on the voltage and inductance of the circuit. The dotted lines indicate that a higher prospective current is needed to saturate a larger fuse. It is shown in Appendix 2 that for any particular metal the saturation current is proportional to the cube root of the voltage, inversely proportional to the cube root of the inductance, and proportional to the $\frac{3}{2}$ power of the cross-section of the element. It is also shown that for single-element fuses it increases as the $\frac{5}{6}$ power of the minimum fusing current; this is illustrated by the experimental curves of fig. 20. If higher fuse ratings are obtained by increasing the number of elements, then the saturation current increases at a somewhat less rate. The saturation current is reduced by pre-heating, so that the duty on the fuse is eased if it is carrying load when the short-circuit is applied.

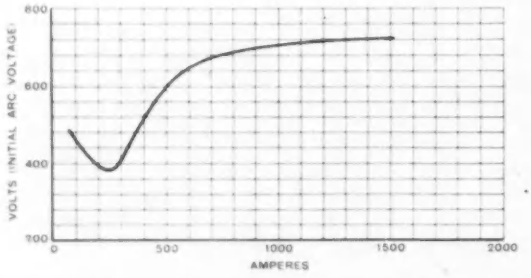


Fig. 4.—Typical voltage/current characteristic of arc in silver-wire fuse.

Anode and cathode—silver. Length of wire 0.47in.
Wire—silver. Dia. of wire 0.0136in.
Filler—silica. No pressure relief.

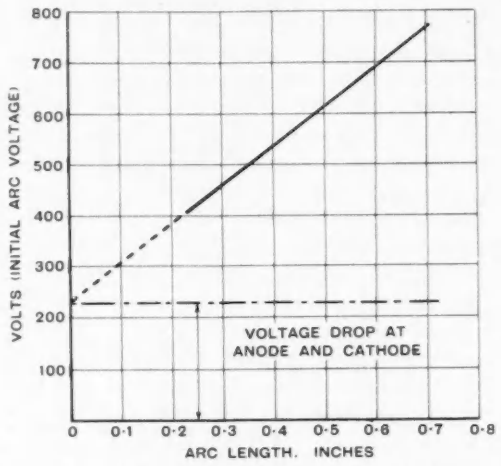


Fig. 5.—Typical voltage/length characteristic of arc in silver-wire fuse.

Anode and cathode—silver. Current 600 amp.
Wire—silver. Dia. of wire 0.0136in.
Filler—silica. No pressure relief.

Operation on Alternating Current.

With alternating current the current-limiting effect is dependent also on the phase instant of the short-circuit. If the prospective current is high or the section of the fuse element small, and if short-circuit is initiated on a rising voltage or near a peak of voltage, the rise of current will be approximately linear throughout the pre-arcing time, so that, as with direct current, the cut-off current is inversely proportional to the cube root of the inductance. (Fuses operating with a substantially linear current rise will, in what follows, be referred to as "quick-acting," it being remembered that "quick action" is a property of the circuit as well as of the fuse.) In a quick-acting fuse in an A.C. circuit of low

short-circuit power factor, the cut-off current is thus proportional to the cube root of the prospective current. The case mentioned above corresponds approximately to a symmetrical short-circuit, as shown in fig. 9(*c*). With a completely asymmetrical short-circuit, fig. 9(*a*), on a fuse of low cut-off current, the pre-arcing time is longer than with a symmetrical, but the converse is the case with fuses of higher rating, as shown in Appendix 3.

Occurrence of short-circuit on a falling voltage in giving rise to an initial minor peak may result in a longer pre-arcing time than for either a symmetrical or a completely asymmetrical short-circuit. An example is shown in the test oscillogram, fig. 2(*a*). Comparing this with fig. 2(*b*) for short-circuit initiated on a rising voltage, it will be seen that the difference in the pre-arcing times nearly neutralizes the difference in the instants of short-circuit, with the result that in both instances arcing commences just before a peak of the voltage wave.

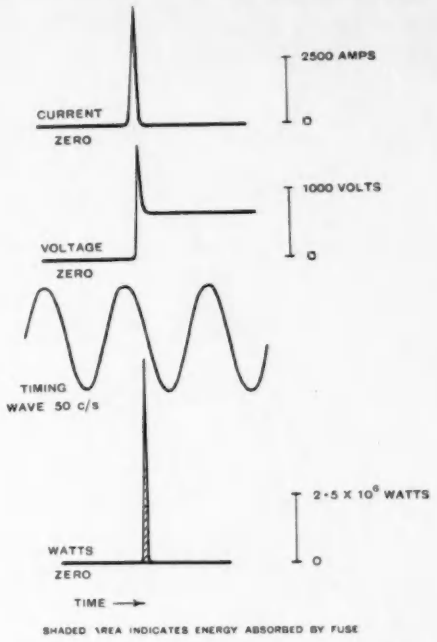


Fig. 6.—D.C. short-circuit on 60-amp. fuse with "straight-through" elements.

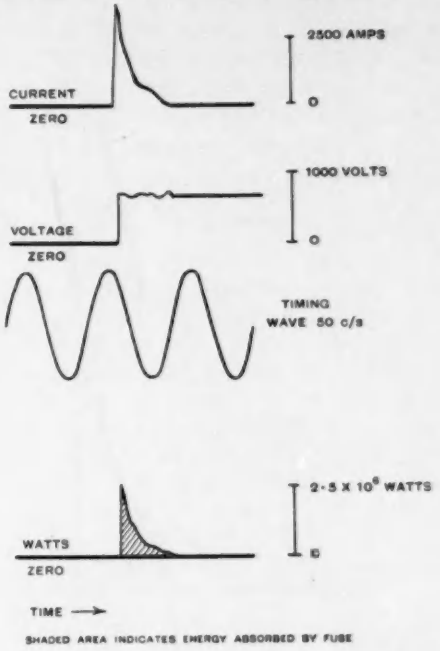
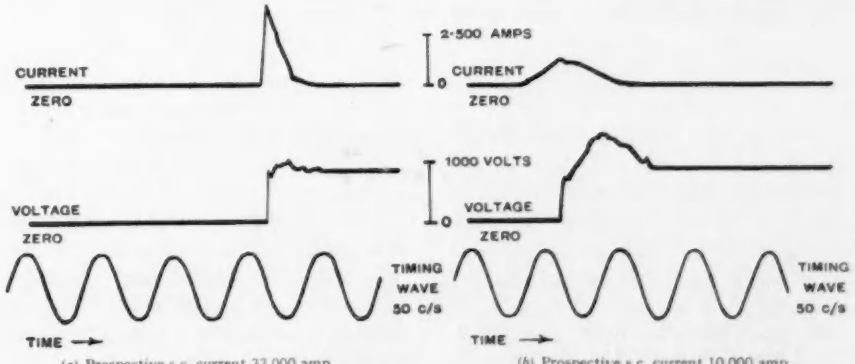


Fig. 7.—D.C. short-circuit on 60-amp. fuse with necked elements.

Fig. 3 gives a family of curves showing the current-restricting effect on alternating current (assumed to be of low short-circuit power factor) for selected ratings from a certain range of cartridge fuses having a B.S. 88 duty rating of 440AC4. The maximum values of peak current shown at the upper ends of the curves result from symmetrical short-circuits, and those at the lower ends from asymmetrical. Corresponding curves for direct current are not possible since in this case the prospective current depends on resistance only, but the peak current depends on both resistance and inductance.



(*a*) Prospective s.c. current 33,000 amp. Circuit inductance 0.2 mH.

(*b*) Prospective s.c. current 10,000 amp. Circuit inductance 6.35 mH.

Fig. 8.—Short-circuit tests on 850-volt 60 amp. fuse, with low and high values, respectively, of circuit inductance.

(5) INVESTIGATION OF ARCING CONDITIONS.
Arc Characteristics.

As the element vaporizes, arcing commences and the presence of inductance, even though of extremely low value, results in the fuse voltage being driven up rapidly to a value which is the highest that the arc column can withstand, and is the arc voltage of the fuse, determining the future variation of current through it. The arc voltage is substantially independent of the circuit constants, and as exemplified by the typical curve of fig. 4, does not vary greatly with current. There is usually a rapid decrease in the voltage immediately after the arc is formed, but this decrease, except in so far as it is associated with a decrease in current, is usually small. The voltage for a given current, filler, and section and material of element, increases with the length of the arc; it appears to be made up of a fixed drop at the anode and cathode, and a drop, directly proportional to length, in the arc stream itself. A typical curve, for the same wire and filler as in fig. 4, is given in fig. 5. Further, the voltage decreases, but only slightly, with increase in cross-section of the element. At final clearance the resistance of the arc path builds up as the temperature falls; the fuse voltage therefore reaches the circuit recovery-voltage in a relatively gradual way, the current correspondingly tailing-off to zero. This method of operation prevents the setting up of high-frequency voltage oscillations.

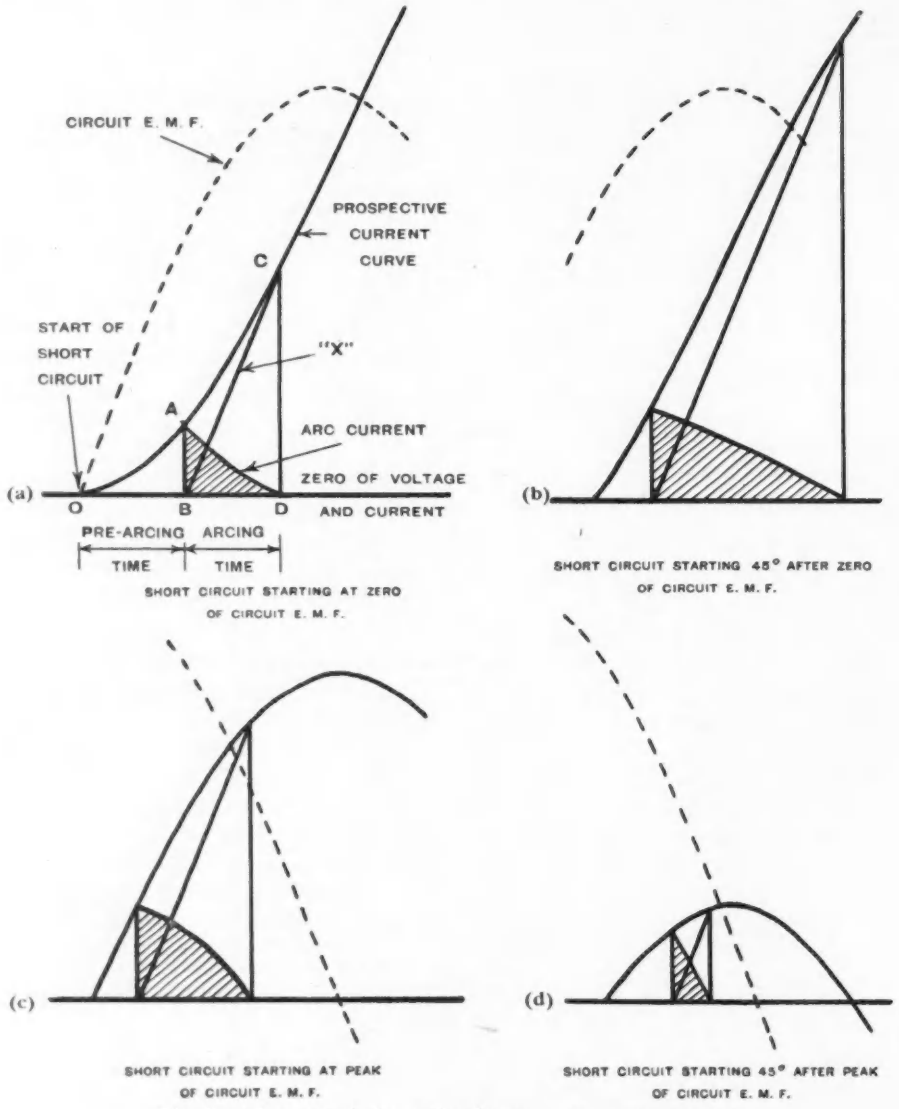


Fig. 9.—Theoretical short-circuits at various phase points.

The core of fused filler remaining after operation must have a satisfactory insulation resistance; other-

wise the resulting leakage current, apart from being in itself highly objectionable, may, while the fuse is still hot after operation, have a sufficiently high value to release appreciable energy in the fuse at a rate which grows as the resistance falls, until a violent "delayed failure" occurs. The breakdown

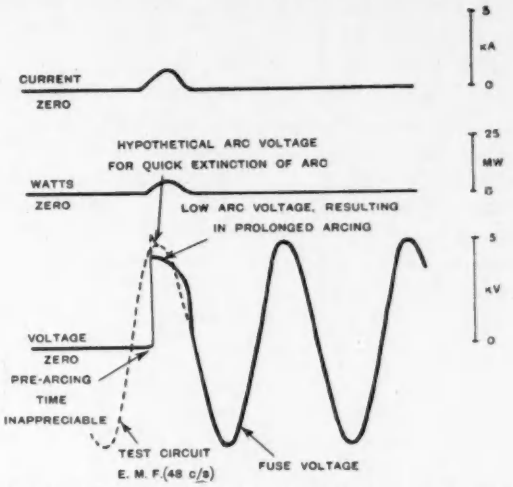


Fig. 10.—Short-circuit test on 3.3 kV, 0.75-amp. fuse at 3.3 kV, 7.5 kA prospective current.

voltage of the fused core is also important and, while of course much lower than that of the pure filler, is, in good designs, of the order of several times the working voltage, and in general is at least as high as that of the insulation of the rest of the system.

Effect of Arc Voltage on Current.

The reduction of current may be considered in the light of the voltage equation :—

Circuit e.m.f. Inductive voltage Arc voltage

$$E + L\frac{dI_{ta}}{dt} + Va$$

Resistance drop in rest of circuit

$$+ RI_{ta} = 0$$

in which the first two voltages oppose extinction, and the second two assist. The resistance of the circuit, which if the fuse is quick-acting exerts no influence during the *pre-arcing* period, can now be seen to have its effect during the *arcing* period by increasing the rate of fall of current, and therefore reducing the arcing time and so the energy developed in the fuse.

An element of uniform section must, for reliable performance, be proportioned to give an arc voltage 1·5 to 2·5 times greater than the D.C. recovery voltage or the peak of the A.C. recovery voltage. On the other hand, a necked element, with its less initial arc length, is usually designed for a ratio of 1·0 to 1·5; the arcing time is therefore usually longer than for the "straight-through" element, though the peak current reached is likely [see Section (3)] to be less. Typical oscillograms of D.C. short-circuit tests on the two types are given in figs. 6 and 7. If a fuse with necked elements is subjected to short-circuit conditions which are severe, for example as the result of a high value of inductance in a D.C. circuit, the arc length increases as the elements melt away from the neck along the reinforced parts, partly because of the heat from the roots of the arc and partly through the ohmic loss in the reinforced part; and the arc voltage increases above its initial value. Typical cases are shown in the oscillograms, figs 8(*a*) and 8(*b*), which are for two D.C. tests of an 850-volt 60-ampere fuse. In the first test the inductance is that of the machines and test leads only, while considerable additional inductance is present in the second. The necked element is seen to have the advantage that it does not develop appreciable over-voltages unless necessary for extinction of the arc.

Calculations of the arcing time for both alternating and direct current on the assumption of a constant arc voltage throughout the arcing period are given in Appendix 4. For alternating current the further

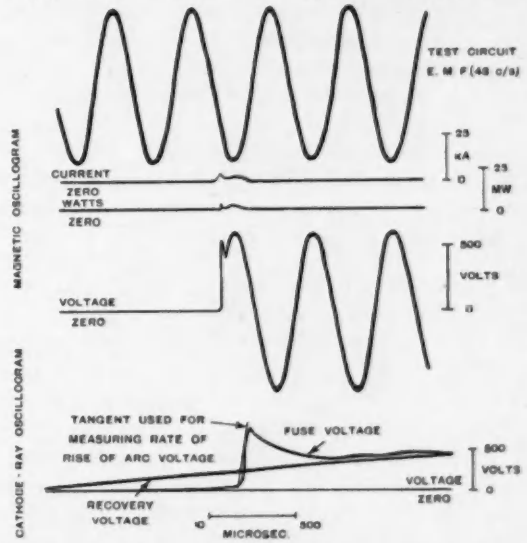


Fig. 11.—Category 440AC4 test on 60-amp. fuse, in circuit of high natural frequency.

No condenser across fuse.
Measured natural frequency = 238 kc./s.
Natural recovery rate of circuit, taken tangentially, at initiation of arcing = 265 V/μsec. (maximum rate is 1.15 times greater).
Actual rate of rise of arc voltage, measured tangentially from oscillogram = 11.2 V/μsec.

assumption is made that the short-circuit power factor is sufficiently low for the effect of resistance to be negligible in comparison with that of inductance, and the results therefore tend to be pessimistic. In this case, however, a simple graphical method[21] of determining the arc current is possible, irrespective of the degree of asymmetry. If A in fig. 9(*a*) represents the point at which arcing commences, the line X is drawn with an inclination V_a/L to meet the prospective current curve at the point C. The perpendicular distance between the line BC and the

prospective-current curve is now plotted to give the curved line AD, representing the reduction of current during arcing.

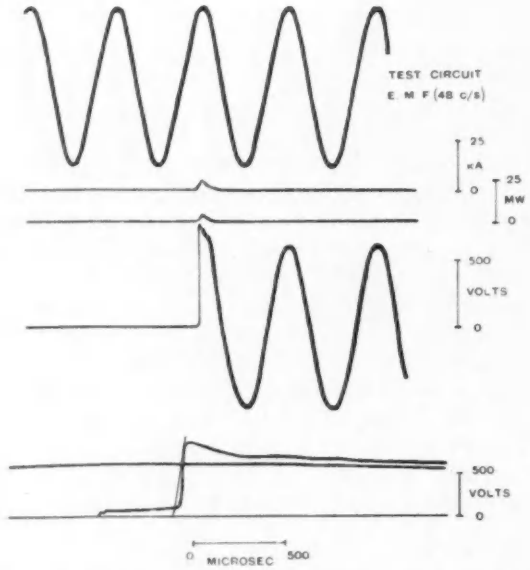


Fig. 12.—Category 440AC4 test on 60-amp. fuse, in circuit of moderate natural frequency.

1.0 μF condenser across fuse.
Measured natural frequency = 19.4 kc./s.
Natural recovery rate of circuit, taken tangentially at initiation of arcing = 55 V/μsec. (maximum rate is 1.15 times greater).
Actual rate of rise of arc voltage, measured tangentially from oscillogram = 12.9 V/μsec.

It is also shown in Appendix 4 that if the arc voltage is equal to the peak of the A.C. line voltage, then the maximum value of dI_{ta}/dt is equal to twice the maximum slope of the prospective-current curve, while for an arc voltage twice the A.C. peak voltage the corresponding maximum rate is 3 times. Thus very rapid reduction of current can only be obtained in fuses developing considerable over-voltages. It may be noted that for any particular fuse, a high A.C. short-circuit value results not only in a short pre-arcing period, but also, on account of the increase of arc voltage with peak current, in a short arcing period. Fig. 9(*a*), together with figs. 9(*b*), 9(*c*) and 9(*d*), are theoretical curves for a fairly quick-acting fuse with an arc voltage of 1·17 times the peak A.C. voltage, the short-circuit being applied at 4 different points in the voltage wave.

If a fuse operating on an A.C. short-circuit develops an arc voltage appreciably less than the system peak voltage, the current continues to increase after arcing has commenced and extinction does not take place until (or substantially until) the system voltage reaches zero. This type of operation can be regarded as intermediate between that of a normal cartridge fuse and that of a circuit-breaker. This is exemplified by fig. 10 for a test on a fuse rated at 3·3 kV, 0·75 amp. The low current rating resulted in the pre-arcing time being so short as to be imperceptible on the oscillogram, but the peak current and arcing time are seen to be excessive. Thus this method of action results in a very poor short-circuit performance.

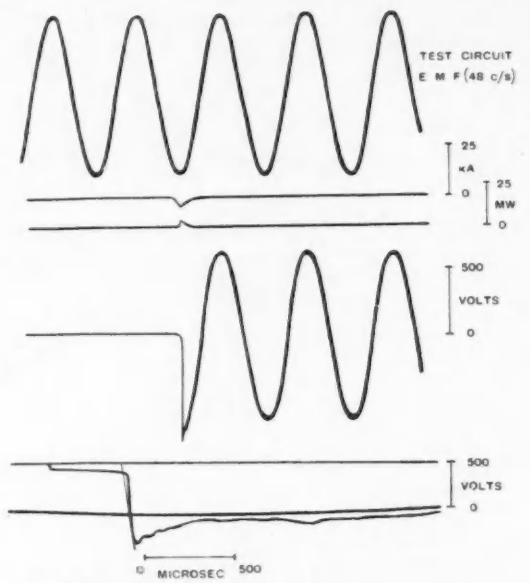


Fig. 13.—Category 440AC4 test on 60-amp. fuse, in circuit of low natural frequency.

15 μF condenser across fuse.
Measured natural frequency = 1.0 kc./s.
Natural recovery rate of circuit, taken tangentially at initiation of arcing, = 2.8 V/μsec.
Actual rate of rise of arc voltage, measured tangentially from oscillogram = 14.9 V/μsec.

Effect of Capacitance.

While circuit-breaker performance may be considerably influenced at the zero pause by variations of circuit capacitance and so of natural frequency, there is in general no analogous action in the case of cartridge fuses. It might be expected that the rate of rise of restriking voltage of the circuit would largely determine the rate at which the arc voltage increases at the instant of vaporization, but this is not borne out in practice. Figs. 11, 12 and 13 illustrate three tests on a certain 60-amp. fuse, all under 440AC4

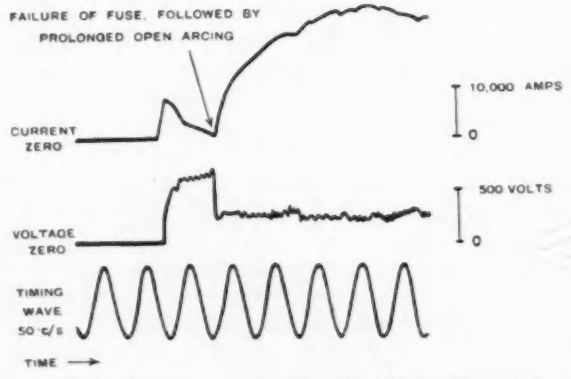


Fig. 14.—Failure of experimental 200-amp. fuse at 600 volts (D.C.).

conditions, but with circuits of widely varying natural frequencies. The cathode-ray oscillograms show fuse voltage, and the corresponding magnetic oscillograms are given for comparison. These tests bear out the general conclusion that, within any ordinary limits, variations of natural frequency have no appreciable effect on performance. It should, however, be pointed out that extreme values of circuit capacitance may in certain cases greatly ease the duty on the fuse.

Operation on Moderate Overloads.

It was recognized many years ago that certain fuses are liable to fail on moderate overload by prolonged arcing.[3] Special care must be taken by the designer to guard against this trouble, which is more prevalent in D.C. than in A.C. circuits and appears to be caused by erratic behaviour of the arc at low

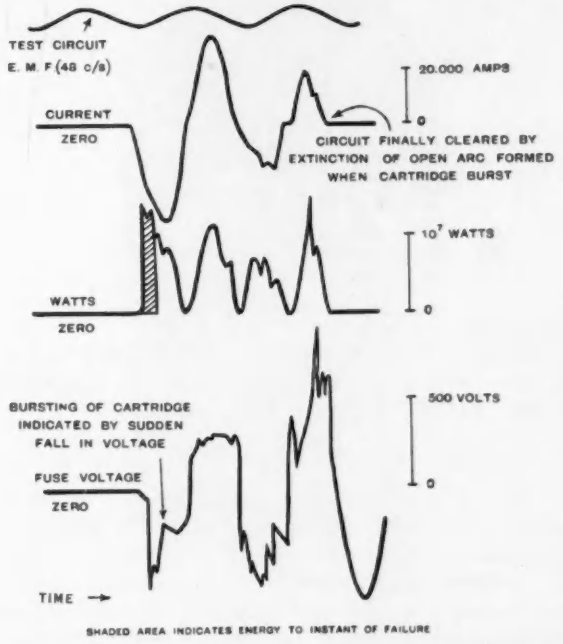


Fig. 15.—Failure of experimental 400-amp. fuse on 440AC4 test.

currents. This so-called "weak range" is less likely to be present in multi-element fuses. It will be seen from fig. 4 that at low currents the arc has a negative resistance characteristic. The result is that in a multi-element fuse the parallel arcs formed on moderate overload are unstable; most of them are therefore extinguished and the resulting increase of current in the one, or perhaps two, remaining arcs causes positive extinction.

Arc Conditions in relation to Breaking Capacity.

It is found that there are two fairly well-defined types of failure, either of which may limit the breaking capacity of a fuse. These occur :—

(*a*) By the energy developed exceeding the limit which the filler can accept, the body usually being split open in a relatively gentle way. This type of

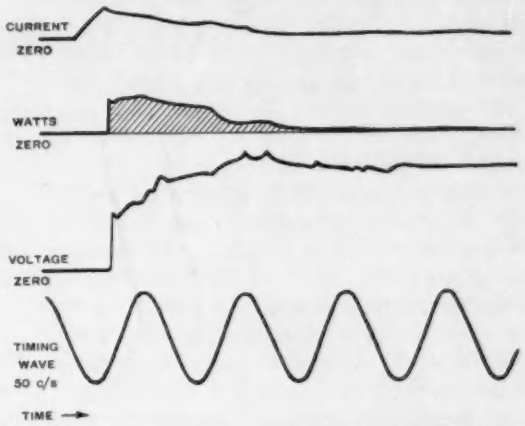


Fig. 16.—Test on experimental 400-amp. fuse at 600 volts (D.C.).

failure results from prolonged arcing caused by excessive voltage or inductance, and is typical of operation in the circuit of D.C. machines since these usually have a moderately high inductance. Fig. 14 is the oscillogram of a test resulting in a failure of this type.

(*b*) By an excessive pressure being developed by the vaporization of the element. On account of the small volume of air in the interstices of the filler, the maximum pressure is applied to the cartridge wall very rapidly, and, in typical cases, within 1 or 2 millisec. from vaporization. If this pressure is excessive, the cartridge bursts violently at an early stage in the arcing period, leaving a large proportion of the filler unfused. The energy supplied up to the instant of failure is much less than the fuse can accept if supplied over a longer period. For example, fig. 15 shows an experimental 400-amp. cartridge fuse failing on a 440AC4 test, the energy supplied to the instant of failure being only 27 kW-sec. Fig. 16 shows, to the same scales, an identical fuse tested at 600 volts direct current, the prospective current being 22,500 amp. and the time-constant 0·013 sec.; this test was successful and the fuse accepted an energy of 111 kW-sec. This second method of short-circuit failure appears, as might be expected, to be the invariable one with certain fuses having weak enclosures. On the other hand, in fuses of good mechanical design it seems to occur most frequently in A.C. circuits of low inductance, resulting in high values of peak current. While the relation between mechanical pressure and the electrical quantities of the circuit is not clear, it may be that failure is related to some limiting value of the product of arc voltage and peak current, *i.e.*, to a power value as opposed to an energy value for the first type of failure.

Lighting Problems in connection with Air Raid Precautions.

By W. R. STEVENS, B.Sc., F.I.E.S. and J. M. WALDRAM, B.Sc., F.Inst.P., F.I.E.S.
G.E.C. Research Laboratories, Wembley, England.

1. INTRODUCTION.

THE basis of A.R.P. lighting in Great Britain is the complete black-out. Interior lighting must be so screened as to be invisible from the ground or the air, and exterior lighting, where permitted, is regarded as an exception to the general rule. Exterior lighting is generally permitted only in certain circumstances for essential operations such as work in docks and railway yards, for street lighting and for essential signs and aids to movement. Only where it is absolutely necessary are higher levels of illumination permitted which can be switched off in emergency. White lines and kerbs have been found valuable in making the best use of the light available, and illuminated signs are recommended in the Lighting Order to guide pedestrians and vehicular traffic.

The lighting of the country in war time is governed by the Lighting (Restrictions) Order issued by the Minister of Home Security under the Defence Regulations. The first Lighting Order, of 1939, was evolved by technical advisers to the Home Office assisted, where they deemed it necessary, by commercial and other laboratories. Shortly before the declaration of war, however, a Joint Committee was set up of the A.R.P. Department of the Home Office, and the Illuminating Engineering Society. This committee appointed many sub-committees, and was able to draw on all the available sources of information connected with lighting in this country. A free interchange of ideas was thus brought about between technical representatives from different laboratories and manufacturers as well as government officials. Some of the work of these sub-committees has been reported in the form of British Standard Specifications, eight of which were published before the end of 1939. These included such complicated subjects as A.R.P. signs, luminescent paints and street lighting.

The effect of the work of the Joint Committee is visible in the new Lighting (Restrictions) Order (1940), issued in January. Reference to such expedients as the use of tissue paper and newspaper as diffusing media are rare; and lighting installations and fittings are controlled by specifications of illumination or brightness, and by reference to British Standard Specifications, to a much greater extent than in the previous Order. In some cases the performance of the fitting is controlled rigidly by the "B.S.I. Mark" scheme, which ensures careful manufacture and testing of the equipment and simplifies the purchase of fittings and the administration of the Order.

It is impracticable to administer the Order on the basis of field photometry at the low levels

Fig. 1.—IES/ARP .02 fitting as made by the G.E.C.

concerned. The engineer may still consider the wording to be vague in parts of the Order, but this is at present presumably unavoidable for administrative reasons.

2. GENERAL PRINCIPLES OF A.R.P. LIGHTING.

By the lighting restrictions ordered in this country, the amount of light which is generally permitted to escape or to be used outdoors is *nil*. In the certain special exceptions mentioned above some exterior light is permitted, but its amount and distribution are very carefully controlled. The problems of A.R.P. lighting are therefore in the use of very small amounts of light in exempted outdoor situations, and in the effective screening of light used indoors. The amounts of light which are permitted outdoors are remarkably minute, particularly in view of the increasing illuminations which it was insisted were necessary just before the war, and their very minuteness brings a whole series of new problems.

Exempted lighting is of two main kinds. In places where essential work is to be carried on outdoors, lighting is permitted to a level which is high for A.R.P. lighting, on the understanding that such lighting is under strict control and is switched off during an air raid. This was also the intention for lighting in shop windows. In other situations,

such as the lighting of streets, signs and shelters, the lighting is intended to remain on during a raid and it is consequently at a very much lower level. When it is realised that the illumination from full moonlight is only about 0·02 ft. candle, that on a clear moonless night it is about one hundredth of this, and that on a cloudy moonless night it is very much less again—of the order of a hundred thousandth of a foot candle—it will be clear why the permitted levels are so low, for in such low illuminations almost any light becomes conspicuous. A light of 0·5 candle can be quite easily seen at a distance of a mile, or about 5,000 ft.; in fact this is the limiting condition for the safe visibility of a signal light at sea in peace time. An air observer who has been for some hours in darkness can see an amazingly small amount of light. Outdoor tasks must therefore be done with illuminations which are far below anything which can be considered

Fig. 2.—A.R.P. shelter location box sign.

adequate, and the design of the lighting resolves itself into finding whether any use can be made, or any amenity gained, from the small amount of light which can be safely permitted. In A.R.P. lighting, therefore, the greatest use must be made of every available lumen, so that the lighting conveys as much information as possible to its users.

In the blackout on a dark night the amount of visual information is unusually restricted and is often quite inadequate; in particular, the *kind* of information on which we are accustomed to rely is often missing. Aids to vision should therefore, as far as possible, give information in the form in which users of the road are accustomed to receive it; otherwise they will have to learn a complete new system of recognition for use in the blackout. For example, in the street we have become accustomed to the well-marked perspective of the scene, by which in fact the more important judgments of distance and speed are made. In the blackout it is often not possible to see enough of the scene to recognise the perspective, and consequently serious misjudgments occur of distance and speed, and of one's whereabouts. Aids to vision should therefore accentuate the features of perspective on which the road user relies; otherwise they may confuse him or, worse, may mislead him. For this reason any system of beacon lights, which appear simply as points of light, is at a disadvantage; for the distance of a point of light which is unrelated to anything else is very hard to judge. If the lights are not on the ground but are raised above it, it is particularly hard to judge their position accurately. In any case, such a system provides few recognisable landmarks. The systems of blackout lighting in this country have therefore generally aimed to give, so far as is consistent with safety, light which will reveal the perspective of things in the way with which the user is familiar, rather than giving him a series of "code" lights, the significance of which he has to learn. In some instances, of course, such beacons and signs are unavoidable; when they are used, an attempt is being made to arrange that they shall be uniform throughout the country so that users will recognise them instantly as familiar signs, in the same way as they recognise standard traffic signs. Uniformity of practice is essential in blackout lighting.

The lighting system must be made to discriminate as much as possible in favour of the user and against the air observer, and this involves many difficulties. With small illuminated objects such as signs, or display cabinets in show windows, the discrimination is fairly easily made by screens which positively prevent the illuminated object from being seen from above. Even here it is sometimes difficult to avoid screening the sign from the user as well as from the enemy, particularly when large screens are impracticable. Where large areas are to be illuminated the problem becomes still more difficult. In some cases, such as in the illumination of streets, the ground observer may wish to see for nearly as far as a low-flying air observer, and the ground observer is not generally so well dark-adapted. Mist is often confined to a layer near the ground, and may hinder the ground observer more than the air observer. But advantage can sometimes be taken of the different points of view of the rival observers, from preferential reflection properties of surfaces, and so on. Naturally there have been many proposals for achieving a discrimination which have had to be examined, and which have proved unsound or impracticable. For example, the use of blue light was strongly advocated; but after some exhaustive experiments its advantages turned out to be mythical. The use of fluorescent materials with various forms of excitation has

Lighting Problems in connection with Air Raid Precautions.

By W. R. STEVENS, B.Sc., F.I.E.S. and J. M. WALDRAM, B.Sc., F.Inst.P., F.I.E.S.
G.E.C. Research Laboratories, Wembley, England.

1. INTRODUCTION.

THE basis of A.R.P. lighting in Great Britain is the complete black-out. Interior lighting must be so screened as to be invisible from the ground or the air, and exterior lighting, where permitted, is regarded as an exception to the general rule. Exterior lighting is generally permitted only in certain circumstances for essential operations such as work in docks and railway yards, for street lighting and for essential signs and aids to movement. Only where it is absolutely necessary are higher levels of illumination permitted which can be switched off in emergency. White lines and kerbs have been found valuable in making the best use of the light available, and illuminated signs are recommended in the Lighting Order to guide pedestrians and vehicular traffic.

The lighting of the country in war time is governed by the Lighting (Restrictions) Order issued by the Minister of Home Security under the Defence Regulations. The first Lighting Order, of 1939, was evolved by technical advisers to the Home Office assisted, where they deemed it necessary, by commercial and other laboratories. Shortly before the declaration of war, however, a Joint Committee was set up of the A.R.P. Department of the Home Office, and the Illuminating Engineering Society. This committee appointed many sub-committees, and was able to draw on all the available sources of information connected with lighting in this country. A free interchange of ideas was thus brought about between technical representatives from different laboratories and manufacturers as well as government officials. Some of the work of these sub-committees has been reported in the form of British Standard Specifications, eight of which were published before the end of 1939. These included such complicated subjects as A.R.P. signs, luminescent paints and street lighting.

The effect of the work of the Joint Committee is visible in the new Lighting (Restrictions) Order (1940), issued in January. Reference to such expedients as the use of tissue paper and newspaper as diffusing media are rare; and lighting installations and fittings are controlled by specifications of illumination or brightness, and by reference to British Standard Specifications, to a much greater extent than in the previous Order. In some cases the performance of the fitting is controlled rigidly by the "B.S.I. Mark" scheme, which ensures careful manufacture and testing of the equipment and simplifies the purchase of fittings and the administration of the Order.

It is impracticable to administer the Order on the basis of field photometry at the low levels concerned. The engineer may still consider the wording to be vague in parts of the Order, but this is at present presumably unavoidable for administrative reasons.

Fig. 1.—IES/ARP .02 fitting as made by the G.E.C.

2. GENERAL PRINCIPLES OF A.R.P. LIGHTING.

By the lighting restrictions ordered in this country, the amount of light which is generally permitted to escape or to be used outdoors is *nil*. In the certain special exceptions mentioned above some exterior light is permitted, but its amount and distribution are very carefully controlled. The problems of A.R.P. lighting are therefore in the use of very small amounts of light in exempted outdoor situations, and in the effective screening of light used indoors. The amounts of light which are permitted outdoors are remarkably minute, particularly in view of the increasing illuminations which it was insisted were necessary just before the war, and their very minuteness brings a whole series of new problems.

Exempted lighting is of two main kinds. In places where essential work is to be carried on outdoors, lighting is permitted to a level which is high for A.R.P. lighting, on the understanding that such lighting is under strict control and is switched off during an air raid. This was also the intention for lighting in shop windows. In other situations,

such as the lighting of streets, signs and shelters, the lighting is intended to remain on during a raid and it is consequently at a very much lower level. When it is realised that the illumination from full moonlight is only about 0·02 ft. candle, that on a clear moonless night it is about one hundredth of this, and that on a cloudy moonless night it is very much less again—of the order of a hundred thousandth of a foot candle—it will be clear why the permitted levels are so low, for in such low illuminations almost any light becomes conspicuous. A light of 0·5 candle can be quite easily seen at a distance of a mile, or about 5,000 ft.; in fact this is the limiting condition for the safe visibility of a signal light at sea in peace time. An air observer who has been for some hours in darkness can see an amazingly small amount of light. Outdoor tasks must therefore be done with illuminations which are far below anything which can be considered

Fig. 2.—A.R.P. shelter location box sign.

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obvious and attractive possibilities, not all of which have been practicable. There does not seem to be any remarkable short cut to the problems of A.R.P. lighting.

3. PROBLEMS OF LOW LEVEL A.R.P. LIGHTING.

(a) Lighting of Essential Work.

The Lighting (Restrictions) Order makes general exceptions to the rule of total blackout, in the matter of such essential services as railways, docks, waterways, aircraft and aerodromes. These services are permitted by the text of the Order to display certain lights and to provide illumination of essential places up to a level of 0·002 ft. candle. This light can be left on during a raid, unless the Chief Officer of Police directs that it shall be extinguished. There is also provision for special exemptions made by order of the Chief Officer of Police, the conditions of which are not detailed in the Order. These exceptions have been made in specific instances which are individually considered, and in such instances illuminations up to 0·2 ft. candle have been permitted, but with the provision that they are under proper control and are switched out upon receipt of an air raid warning.

For most of these purposes a general lighting installation is required, much the same as is installed in peace time at docks, etc., but giving illumination at a much lower level. It is important to ensure that the general permitted level is not exceeded and that no light is permitted above the horizontal. Three British Standard Specifications have been prepared to cover fittings for the three levels of 0·002, 0·02 and 0·2 ft. candles (BS/ARP. 16, 20 and 21) which specify the necessary characteristics for the three types of fitting. The specification includes as examples designs which comply with the requirements, three different designs being provided of each type to be used for three ranges of mounting height. A typical G.E.C. fitting for 0·02 ft. candle

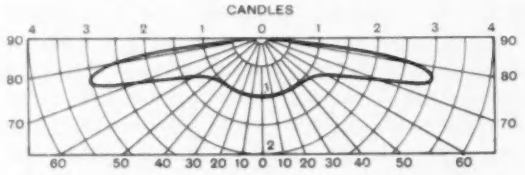

Fig. 3.—Polar curve showing light distribution in vertical plane from an IES/ARP .002 fitting for 15 ft. mounting height.

made to the Specification design, is shown in fig. 1. This range of fittings uses 100 watt lamps. The necessary change for different mounting heights consists in changing the reflection factor of the finish of the reflector, which is matt and either black or one of two shades of grey corresponding to mounting heights of 10, 15 and 20 ft. For 0·002 ft. candle the design is similar and the lamp wattage is reduced to 15 watts, and for 0·2 ft. candle a different form of reflector without a lower cup is used with a 15, 25 or 40 watt lamp according to the mounting height. In all these fittings, the quoted illumination refers to the approximate average illumination in an installation of a number of the fittings mounted at a spacing-height ratio of 4 : 1 for the two lower values and 2 : 1 in the highest value.

All these fittings require careful manufacture and installation if the permitted values are not to be exceeded, and experience with them has been valuable in later designs of other fittings, for example those for street lighting. It is remarkable that a

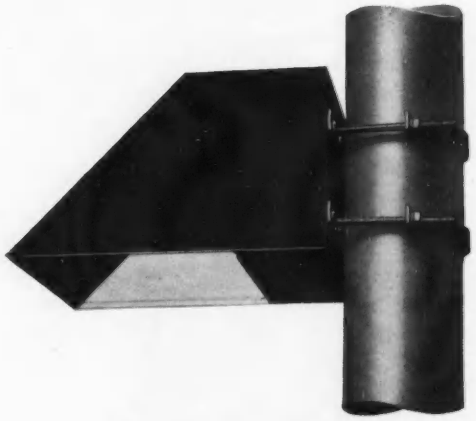

Fig. 4.—A.R.P. angle fitting.

polar curve such as that of fig. 3 should be produced with so simple a construction; it is only possible because efficiency is not important. With an efficient fitting a complex refractor would be required to produce such a distribution. This design has, however, the disadvantage that a part of the light distribution is produced by direct view of the lamp through the gap between the shade and the cup, and the light distribution is therefore sensitive to changes in the lamp position.

For most purposes it is sufficient to consider illumination on a horizontal plane. In some building operations, however, it is also important to consider the illumination on a vertical plane, for example when a wall is being built. A special fitting has been developed by the G.E.C. for this purpose, intended to be mounted at a height of 20 ft. and at 18 ft. from the face of the wall, and giving an illumination of not more than 0·2 ft. candles (fig. 4). The same fitting can also be used for the illumination of large horizontal surfaces from posts mounted at the edge of the surface, without the danger of light spreading beyond the surface; and it can be mounted against a wall so as to illuminate the ground without lighting the wall.

(*b*) *Signs.**

Two classes of illuminated signs are used in blackout conditions: route number and direction signs for the guidance of traffic, and signs used in connection with the defence services giving the direction to, or the location of, such premises as air-raid shelters, first-aid posts, hospitals, wardens' posts, and the like. The official requirement for both types is that they should be legible at 100 ft. and inconspicuous at 250 ft. in the absence of rain, fog, mist and moonlight. In the Home Office Memorandum on "Aids to the Movement of Traffic to be Installed on Roads and Streets in the Absence of Street Lighting," but not in the 1940 Lighting Order, more precise information was given of the performance of existing road traffic signs necessary to fulfil this requirement. Details were given of the route number signs, which were new, in which the brightness of the white letters was permitted to reach 1 candle per sq. ft. (3·1 e.ft.-c.). The larger black-on-white direction signs, as erected by the R.A.C., were permitted to be illuminated to 0·1 candle per sq. ft. Signs which could be recognised without being read, such as "Keep Left" signs at guard posts and roundabouts, were permitted to have a brightness of 0·1 candle per sq. ft. Screening of the smaller signs was required. These details are not repeated in the 1940 Lighting Order, but they are generally worked to; a typical G.E.C. lantern for an R.A.C. sign is shown in fig. 5. It uses a 15 watt lamp with an optical system similar to that described below.

For signs of the second class a complete series of designs has been worked out and specified in BS/ARP. 32, giving the forms of lettering and if illuminated the brightness which can be permitted. In the latest edition of the specification, typical designs for fittings for illuminating these signs have been given, together with very complete provisions for illumination, uniformity of brightness, and testing of signs of the front-illuminated and of the box type. The B.S.I. Mark scheme is available for illuminated signs of this kind.

These signs form a complete system of guiding which has been the subject of a good deal of research into their legibility under blackout conditions. The direction signs are generally made with their length horizontal, and the location signs with their length vertical, and the general design is such that the sign can be recognised even if it cannot be read (figs. 2 and 13). The large letters or symbols are important; visual acuity under blackout conditions is very poor.

The Order refers also to the lighting of guard posts, refuges and other obstructions. Many of these use oil hurricane lamps with a mask to give the specified "St. Andrew's Cross." These lamps are very expensive to run, since they require constant maintenance and daily collection and replacement. It has been found that small electric signs, taking only 15 watts, enable a saving of several hundreds of pounds per annum to be made in a large borough in respect of labour, paraffin and petrol (see fig. 6).

(*c*) *Street Lighting.*

The provision of some street lighting during the blackout has been one of the most intricate of all the A.R.P. lighting problems. From the point of view of public need, there is no doubt that it is necessary. On really dark nights, traffic, particularly pedestrian traffic, is utterly lost; and all social and educational intercourse which requires people to go outdoors is brought to a standstill. The loss of life

Fig. 5.—Fitting for lighting of R.A.C. sign.

owing to traffic accidents may easily reach proportions which compare with air raid losses. The authorities are therefore faced with the very difficult problem of drawing the line between the needs of the users of the road and the danger, which is very real, of disclosing valuable information to the enemy. Much work has been done, both in observation from aircraft and in laboratory experiment, to determine the amount of light which can be tolerated from the point of view of air observation. The problem is extremely complicated and cannot be discussed in any detail; but after many experiments it was

* Since this article was written new regulations have come into force under which signposts and the display of place names are forbidden.

decided to permit a certain very low level of street lighting. The level had to be extremely low, for it was found that under good conditions on a dark night, air observers can see unexpectedly minute amounts of light when so well-defined a pattern as a system of roads is in question. Obviously such a pattern is capable of giving intelligible information to aircraft much more readily than are individual lights which may or may not be recognisable. For street lighting, the requirements have been issued in the form of a British Standard Specification (BS/ARP.37) in which the polar distributions of the fittings are laid down between suitable limits, and the permissible mounting heights and spacings are specified. The A.R.P. street lighting specification goes, in fact, far beyond what was contemplated in any peace-time street lighting specification. The general level of illumination on the road is to be of the order of 0·0002 ft. candle, and at no point more than 0·0004 ft. candle. It is necessary to provide as far as possible for the use of existing columns and mounting heights, but the alteration of existing fittings has not generally been adopted. In order to check compliance with the specification the machinery of the B.S. Mark has been adopted as explained below; the whole specification is in practice very rigid and calls for care and skill in design and manufacture if its provisions are to be fulfilled.

The very low levels permitted have disappointed those who expected something like peace-time street lighting. The specified lighting is not to be expected to be useful except when all else has failed—that is, on very dark nights and in the absence of much lighting from traffic. On busy streets with much vehicle lighting, or when there is moonlight, its contribution is negligible. But in really dark conditions it is of great value in permitting people to find their way about without difficulty, to see kerbs and obstructions, and to have confidence in going about at night, which is the function which it was intended to fulfil.

The provision of the lighting fittings has been a considerable task. It has been necessary to develop many different designs, to provide for various mounting heights and spacings (the specification recognises four distinct light distributions) and various wattages of lamps. Some typical G.E.C. designs are shown in figs. 16 and 19. In this case, the specification does not give typical designs, each manufacturer being free to develop his own so long as the specification is complied with. Some of the problems of the fitting design are referred to later.

(*d*) *Shop Window Lighting.*

The provision of lighting in shop windows which will be of some use and which will not in the aggregate give away information to the enemy presents many difficulties, but in this instance they are mainly the difficulties of specification and of administration. To light any one display safely is not difficult to a competent engineer, but the average shopkeeper is not so qualified; and there is so wide a variation in the types of window and of display that it is difficult to lay down provisions which will be generally satisfactory. A British Standard Specification (BS/ARP. 35) provides for standard display cabinets in three sizes which can be used in shop windows; but before these cabinets were produced commercially an alternative in the form of a very simple lighting fitting was put forward by the Ministry of Home Security. This has been widely used, but not always made or used according to the Ministry's recommendations, and the general results have been rather irregular.*

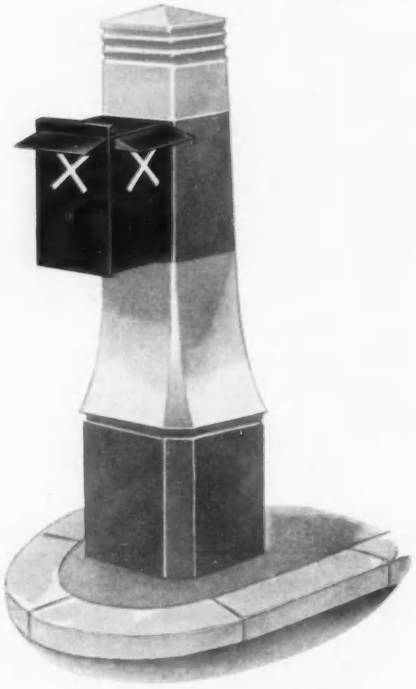

Fig. 6.—Electric refuge fitting.

Illuminated signs as used in peace time are not permitted by the Lighting Order to be exhibited outside premises either by day or by night. It is permitted, however, for shops, hotels and places of public entertainment to use small illuminated signs, which are generally used to give the name and business of the shop and to indicate that it is open. These signs are strictly limited by the Lighting Order; the letters must be light on a dark background; their brightness and total area are limited, and the total extent of the complete sign is also limited. The signs must be within a window or doorway on the ground floor, and the number of

* No shop window lighting is at present permitted.

signs in given premises is limited. Shop signs are intended to be inconspicuous at 100 ft., as distinct from traffic and other signs which are to be visible at 100 ft. and inconspicuous at 250 ft.

(*e*) *Vehicle Lighting.*

Lights on vehicles have been reduced by reducing the power of sidelights and by requiring that headlights be fitted with a mask having specified characteristics. The recognised mask, which is widely used, involves perhaps the closest control of all the A.R.P. lighting devices, and requires great care in manufacture and fitting. The proper control of vehicle lighting is of importance, and sidelights are even more important than headlights, because they emit light up to a considerable angle. Even if a headlight is tilted slightly upwards, the cut-off of the mask is so sharp that an aircraft could not see the light except when it was a great distance away; but a sidelight emitting two or three candles at 50° or 60° to the horizontal can be seen from the air very easily. It is also necessary to limit the candlepower of the headlight both in distribution and in intensity so that it does not produce an illuminated patch on the ground bright enough to be recognised from the air. The original specification for the mask issued by the Ministry of Home Security was sufficient to enable masks to be made, but experience has shown that there are differences between masks made to this specification which indicate a need for more rigid control, particularly of the diffusing material. A good many masks have been altered improperly by their users so as to give more light than is permitted. The British Standards Institution has published a Specification for headlights on tramcars, which includes an illustrative design fulfilling the requirements.

(*f*) *Luminescent Effects.*

There have been many proposals to use luminescent materials for the purposes of A.R.P. lighting, and they have many attractive properties. The two most important are that they provide a convenient way of producing a very low brightness, without involving stray light, and that certain materials have the property of continuing to glow after the irradiating source has been removed. For some purposes, therefore, they hold out the prospect of providing a simple safety indication if the electric supply fails. There are, however, other considerations which affect their use. First, the luminescent devices themselves and the lamps used to irradiate them, if ultra-violet irradiation is employed, are both comparatively expensive; and the scheme is therefore applicable only when the problem cannot easily be solved by more straightforward means using ordinary lamps. Second, the materials which have the greatest fluorescent brightness have a comparatively short period of afterglow; their brightness falls rapidly to values which are too low to be noticed by persons who are not dark-adapted. Other materials are available, however, with a very much longer afterglow period—though of lower initial brightness—which can be used with effect if the supply fails (fig. 7).* Even so, their brightness is rather low for persons who have just left a lighted room, and care is required in applying the materials at present available if they are to have a long life. These materials are, however, interesting in that they are activated by visible light as well as by ultra-violet, and can be used with daylight or ordinary lighting. Ultra-violet lamps are liable to cause discomfort owing to fluorescence of the eye itself; they also sometimes occasion difficulty by unexpectedly causing other materials to fluoresce. It was found for example, in some experiments on the use of fluorescence in street aids to movement, that certain types of car safety windscreens fluoresced strongly enough to make the car difficult to drive.

For these reasons the application of luminescent materials to blackout lighting has developed slowly. The most promising applications are those in which the phosphorescent (afterglow) brightness is used for observers who will remain in the dark with the

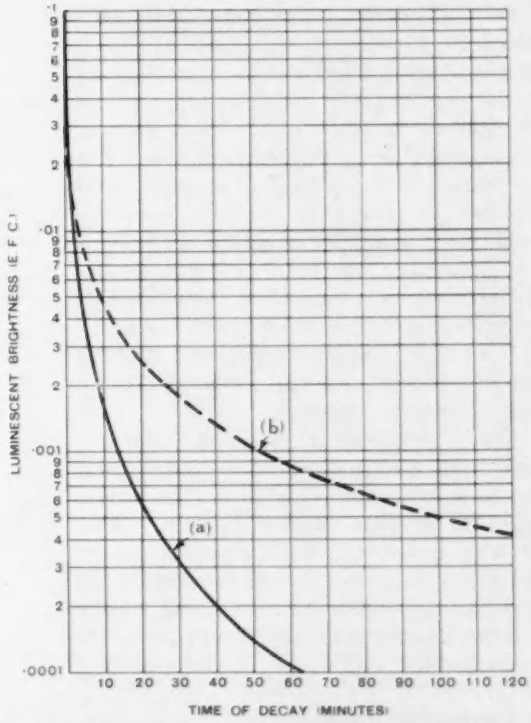

Fig. 7.—Curves of decay of luminescent brightness of (a) ZnS.Cu phosphor; (b) Alkaline-earth sulphide phosphor; after irradiation under BS/ARP. 18 conditions.

* The Photometric Properties of Some Luminescent Materials W. E. Harper, B.Sc., Ph.D., Margaret B. Robinson and J. N. Bowtell B.Sc. Trans. Illum. Eng. Soc. (London) Vol. 5, No. 5, pp. 57-69. June, 1940.

luminescent material, so that as the brightness of the material falls, the sensitivity of the eyes increases as they become dark-adapted. Such applications are the use of luminescent instrument dials and controls, in places which are not blacked out, in conjunction with ultra-violet lamps; and the provision of luminous panels and signs in shelters and similar

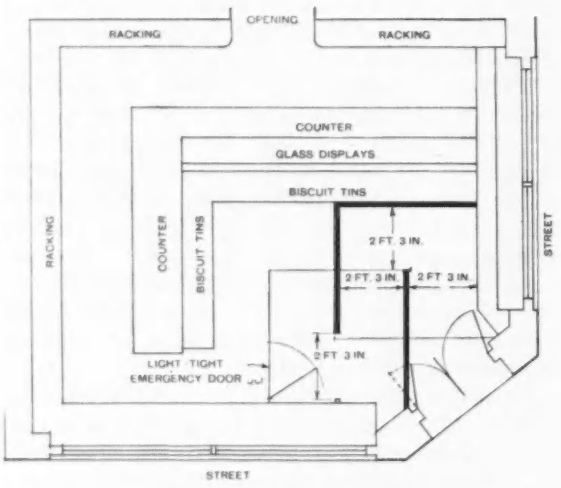

Fig. 8.—Light trap (Reproduced by permission of the British Standards Institution).

places. In general, however, these problems are solved by blacking out interiors properly, so that normal lighting can be used in comfort, and by the regular provision of standby lighting for shelters to cope with supply failures. Nevertheless the use of luminescent materials is a valuable further standby. A specification covering the properties and the testing of luminescent materials intended for use in A.R.P. lighting has been prepared by the British Standards Institution (BS/ARP.18) which covers the two main types of luminescent material, namely the higher brightness shorter afterglow and the lower brightness, longer afterglow materials.

While luminescent materials have not been much used in official signs and the like, they have been quite widely used for private signs and for shop window displays. With the wide range of colours available, a very attractive display can be made, which is the more striking because the background appears quite black and the source of the brightness is not apparent.

(*g*) *Torches and Handlamps.*

The coming of the blackout has brought an enormous increase in the use of torches, and regulations have been introduced to restrict their power and use. A powerful torch can, of course, be seen on a dark night for many miles. A further British Standard Specification (BS/ARP.3) gives the performance specification for handlamps for civil defence use, in which the use of concentrating reflectors is not permitted and there is a restriction upon the candlepower of the handlamp. There have been again several suggestions for special torches, such as torches which automatically extinguish when turned above the horizontal; torches emitting ultra-violet radiation for use with special fluorescent signs, and so on. Such devices have been found to be on the whole impracticable, generally because they can only be used under the special conditions for which they are designed. No one wishes to have to carry two torches, one for indoor and one for outdoor use; and special devices of this kind may only be an exasperation in practice.

4. PROBLEMS OF HIGH LEVEL (INTERIOR) LIGHTING.

(*a*) *Mechanical Screening.*

The problems associated with interior lighting are mainly mechanical. Whether a factory should be blacked out by day as well as by night depends largely on the relative costs of the extra energy required during the time when daylight would normally be used and the capital and maintenance costs of a system of blinds. It is generally felt to be more pleasant to have natural lighting where possible and some experimenters even claim a physiological

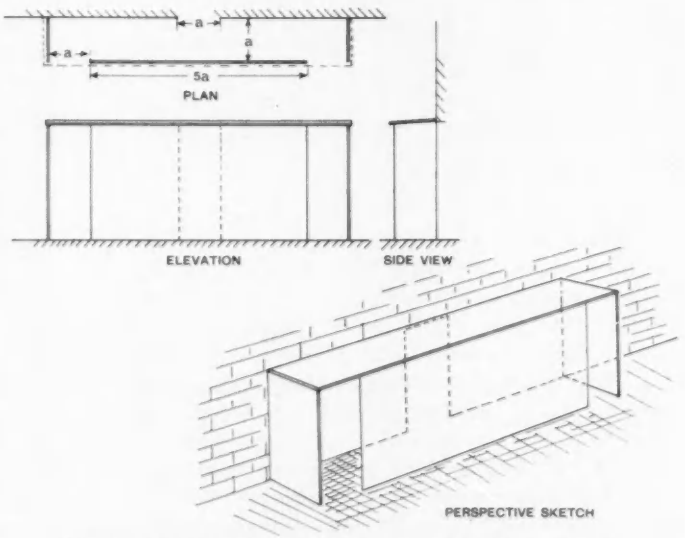

Fig. 9.—Light trap (Reproduced by permission of the British Standards Institution).

benefit; but substantial blackout screens, particularly when they are designed to operate when the glass is broken, are usually expensive to install and often take a considerable time to put up and take down. On the other hand windows can be boarded up

permanently comparatively easily, and a modern lighting installation can provide very good working conditions.

(*b*) *Light Locks.*

A problem associated with all interior lighting systems is that of preventing the escape of light when doors are opened. Light locks for this purpose are dealt with in BS/ARP. 15, and consist essentially

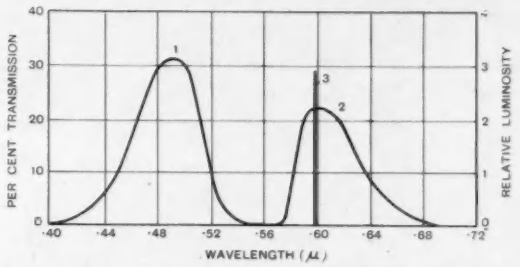

Fig. 10.—Complementary Colour Lighting. Curve 1, Transmission of typical blue lacquer; curve 2, Relative luminosity of amber lamp (tungsten filament); curve 3, Sodium yellow line (not to scale).

of passages having dark walls and ceilings and with two right angled turns so arranged that all light from the interior must suffer at least one reflection from a dark surface before escaping into the street. This specification also gives a number of special arrangements of particular value in industrial premises showing the use of swing doors and opaque curtains. Figs. 8 and 9 are taken from the specification.

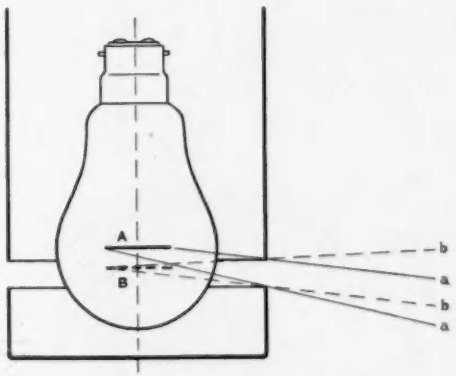

Fig. 11.

(*c*) *Complementary Colour Lighting.*

The only serious attempt which has been made to utilise daylight and artificial light without movable shuttering is that usually known as complementary colour lighting. In this system the windows are painted with a special blue lacquer and orange-coloured artificial light is used. The colours are so chosen that although the blue lacquer transmits some daylight, it is practically opaque to the artificial light which is produced by sodium or tungsten filament lamps in special coloured bulbs. Spectral transmission curves of a typical lacquer and the spectral distribution of sodium and tungsten lamps and filters are given in fig. 10.

The system has, however, the following disadvantages:—

(1) In the event of a bomb falling in the neighbourhood of the building it is probable that some of the glass will be shattered, and the building will then be out of commission until the damage is repaired.

(2) The colour both of the transmitted daylight and of the artificial light is pronounced. By day the light is a definite blue, and most observers have found it an unpleasant light by which to work. The colour of the artificial light is either that of sodium light or (when filtered tungsten filament lamps are used) a deep orange. Any work involving colour discrimination would be impossible under the system.

(3) It is found that with commercially available materials, the daylight transmission of blue lacquers having a sharp enough cut-off to obscure all the orange light, is so low that artificial illumination would be required for many more hours than if removable blinds were used. The transmission to daylight of the best blue materials is of the order of 6 per cent to 10 per cent. The artificial light sources are also much less efficient than normal lamps would be; the efficiency of tungsten lamps in the special bulbs is about 25 per cent, and that of sodium lamps about 60 per cent of normal efficiency.

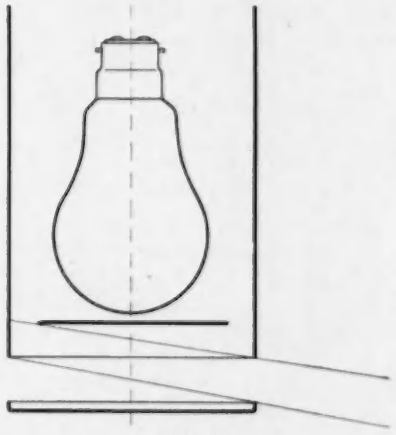

Fig. 12.

Nevertheless there may be places in which the system could be used with advantage, for example, a store-house, corridor, or packing-shop where colour discrimination is unimportant and which is remote

from areas where heavy bombing is expected. The system has been tried on public service vehicles, but has not found favour generally.

4. DESIGN AND TESTING.

(*a*) *Design.*

At first sight, A.R.P. lighting fittings seem too simple to call for much design; most of them are small metal boxes with screens which seem to present few problems. In fact, the requirements of light distribution are strict, and the need for reliability is hardly less than in peace-time equipment. The fittings must produce the light distribution with as few parts as possible; they must be simple to make; they must not depend for accuracy upon features which are liable to variations; they must not be liable to derangement in service, nor easily broken. They should preferably depend for obscuration on the opacity of a piece of metal rather than on the low reflection factor of black paint. It is important that they should operate with standard lamps; for any successful A.R.P. lighting fitting will be used in large numbers, and it is important to avoid a demand for some special lamp of which the industry does not generally carry large stocks. Finally, they must sell for a few shillings.

The chief design method used for A.R.P. fittings for exterior use has been that of obstruction. The illumination levels concerned are so low that a 15W G.L.S. lamp generally provides far more light than is required, and it is often difficult to reduce this to the required values without over-elaborate screening devices. Many of the requirements of peace-time fittings apply also to A.R.P. fittings. Robustness and reliability are particularly important, and it is very desirable that equipment should not be sensitive to small changes in lamp filament position. For this reason it is often undesirable to design fittings in which a small hole or slot controls the light output by direct view of the filament or lamp bulb. In fig. 11 for example, a shift of light source from A to B which may arise from a combination of the tolerances on the lamp, holder and fitting, shifts the emergent beam from *aa* to *bb*. In fig. 12, however, in which the slit sees only a white diffusing surface, the lamp filament position is much less important. These principles of design can be seen in one of the G.E.C. A.R.P. signs illustrated in fig. 13 and shown diagrammatically in fig. 14. The light from the lamp falls on an opal window forming a secondary source which is screened to give an even distribution of light on the face of the sign. Fig. 2 shows another A.R.P. sign in the same range.

Fig. 13.—A.R.P. shelter direction sign.

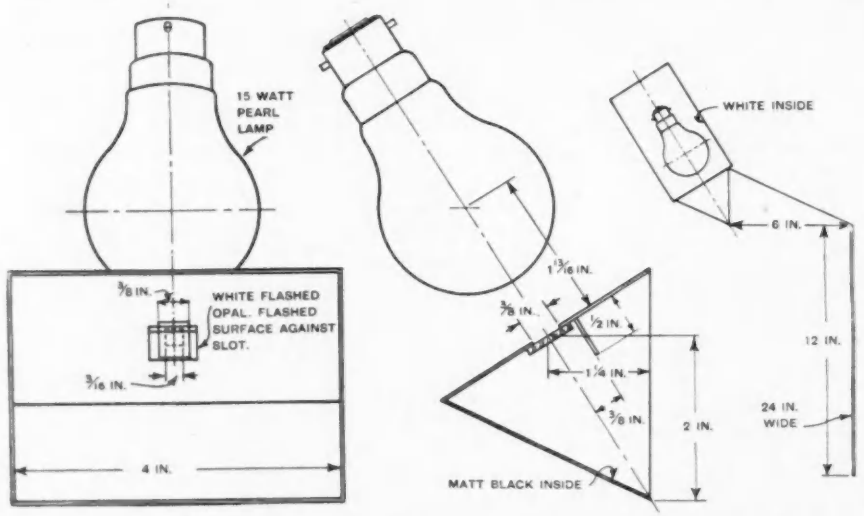

Fig. 14.—Construction of fittings for lighting A.R.P. location and direction signs. (Reproduced by permission of the British Standards Institution).

The G.E.C. A.R.P. street lighting fittings also provide good examples of design by obscuration. These units comply with the requirements of BS/ARP. 37 which defines the performance in terms of four sets of polar-curves of light distribution. Fig. 15 shows the limiting curves for fittings intended to be mounted between 14 ft. and 19 ft. high and not less than 100 ft. apart. Curve A

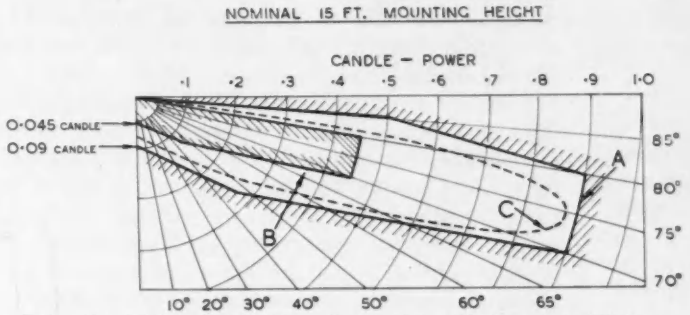

Fig. 15.—Light distribution limits for A.R.P. street lighting fittings, 15ft. nominal mounting height. (Reproduced by permission of the British Standards Institution).

gives the upper limit values and curve B the lower limits; the actual distribution must lie between these curves for any vertical plane through the fitting (*e.g.* curve C).

Two main designs have been developed by the G.E.C., one group for 15W and 25W lamps, and the other for 40W and 60W lamps. This group is intended for those who prefer the more robust filaments of the larger lamps. For fittings mounted at a height of 20 ft. the reduction in maintenance and replacement costs may offset the increased cost of current and of lamps.

Fig. 16.—15 watt street lighting fitting.

The 15W lamp fitting is illustrated in fig. 16 and is shown diagrammatically in fig. 17. It consists of a cylindrical lamp-house (A) white painted inside to which is attached an opal cylinder (B) the upper portion of which is surrounded by a metal cylinder (C) having a number of holes and slots. Below this is a tray with a small opal-covered aperture (D). Above the horizontal all light from the fitting is cut off by the skirt (E). From the horizontal down to 75° the opal cylinder comes into view at a rate determined by the size of the skirt relative to the remainder of the fitting until at 75°, which is the peak direction, a large unobstructed area of opal glass produces the maximum intensity of the fitting. Below this angle the shape of the curve is controlled by the bottom tray and the particular arrangement of slots and holes surrounding the upper part of the opal cylinder. The small hole in the tray gives the correct intensity vertically downwards, its effect becoming smaller at higher angles. Fig. 18 shows the resultant curve obtained. Small variations in lamp light centre length (such as are permitted in British Standard Specification 161), have little effect on the fitting performance for the reasons stated above.

In addition to the various designs of the fitting proper, it is necessary to provide for its fixing to many different designs of existing lanterns. The fitting must be rigidly held; it is not satisfactory to rely upon an adapter screwed into the original lampholder. The fitting illustrated has been made with various spinnings or arms by which it can be inserted into the globe or refractor ring of the lantern, or into a panel, or it may be separately fixed to a bracket in various ways (fig. 19).

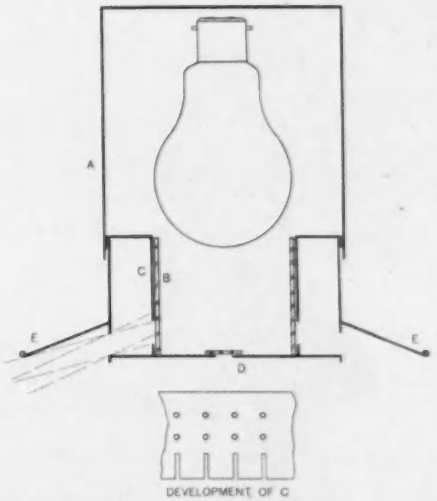

Fig. 17.—Principle of construction of G.E.C. street lighting fitting.

(*b*) *Testing.*

Street lighting fittings must bear the B.S.I. Mark before they may be erected. This marking scheme ensures accuracy and uniformity by control of

individual parts of fittings as well as of the final product. For any one design the proportion of manufactured fittings to be checked, and the permitted tolerances are specified: the B.S.I. reserves the right both to purchase fittings on the open market and have them checked by an independent testing station, and to examine the results of tests made by the manufacturer. By the terms of the B.S.I. licence issued in respect of the fitting shown in fig. 16 every spun metal part and 1 per 100 stamped parts of the optical system is checked by "go" and "not-go" gauges. The gauges must themselves be checked for accuracy at least once a fortnight. Fittings are jig assembled with a general order of tolerance in dimensions of 0·005 inch, although some dimensions have a tolerance of only two-

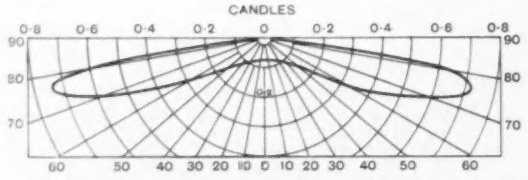

Fig. 18.—Polar curve showing light distribution in vertical plane from G.E.C. street lighting fitting.

thousandths of an inch. The opal cylinders are all checked in a device shown diagrammatically in fig. 20. The cylinder is placed on a turntable which projects slightly outside a blackened box. A tungsten filament lamp is situated slightly below the opal, and illuminates it through a large hole in the turntable. Light from the illuminated opal cylinder is allowed to pass through a horizontal slit about $\frac{1}{4}$ in. wide and on to a photo-electric cell 48 ins. away. The cell is connected to a galvanometer whose deflection is recorded. The relative positions of lamp and cylinder are approximately those in an actual fitting, and the test apparatus records, therefore, not opal transmission, but a figure of merit obtained in conditions similar to those found in fittings. By rotating the turntable the performance of the opal is checked in all directions. The variation allowed in the figure of merit is ± 10 per cent.

The most conclusive test of all, however, is the light distribution of the completed fitting which is determined at the G.E.C. Research Laboratories for about 1 per 100 fittings in a semi-automatic distribution photometer* in which a carefully screened photo-electric cell rotates round the fitting under test. The mirror of a galvanometer connected to the photocell projects a cross-wire on to a sheet of polar-curve paper which is coupled to the photocell arm and rotates with it. When no light falls on the cell, the image of the cross-wires is at the centre of the polar-curve paper, but light from the fitting produces a proportional deflection. By plotting the positions of the cross-wire image as the cell is rotated round the fitting, the light distribution is recorded. The photocell is 3 ft. from the fitting and the deflection produced is of the order of 20 cms. per candle. Great care is required in setting up and calibrating the photometer; the high sensitivity obtained demands a particularly stable galvanometer and careful screening is vital when the maximum illumination falling on the photo-electric cell is of

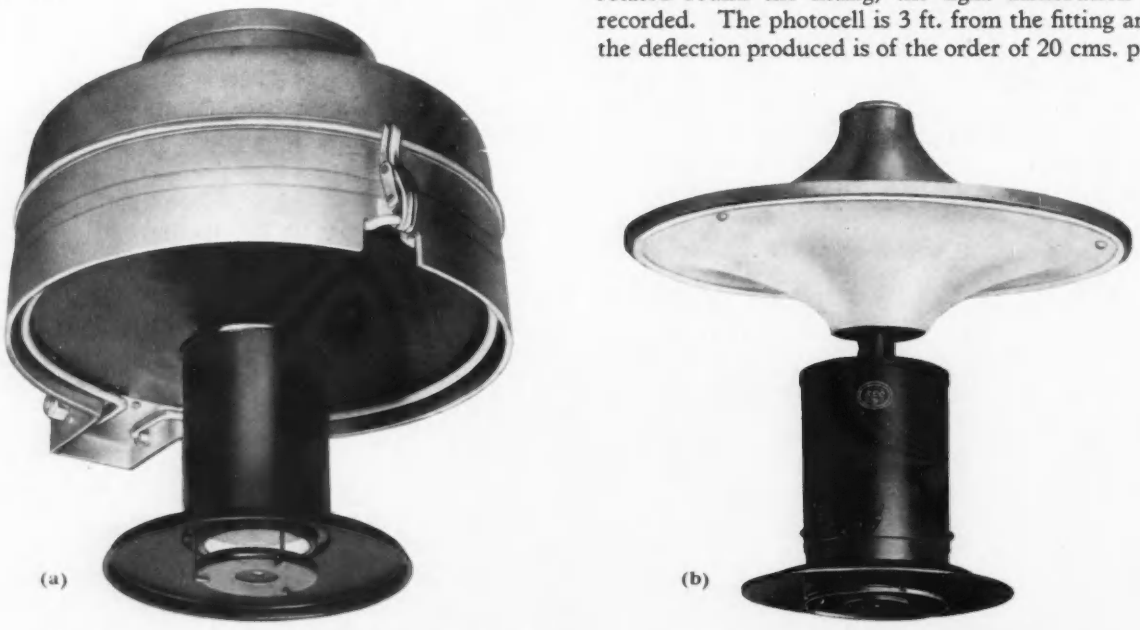

Fig. 19.—(a) and (b) G.E.C. street lighting fitting showing various types of attachment to existing lanterns.

* Wilson and Weir, J. Sci. Insts. 1934 Vol. XI. No. 4. p. 114.

the order of 0·1 foot-candles with a minimum less than 1/10 of this. It is important that any visual measurements associated with the calibration be made with comparison lamps of the proper colour. The peculiar behaviour of the eye to colour differences at low levels of brightness (the Purkinje effect) is such that if the proper precautions are not taken the whole experiment may be vitiated.

When the instrument is set up and calibrated, however, a polar curve of light distribution can be determined in a few minutes. During the five months from December, 1939 to April, 1940, the total number of polar curves recorded at the Laboratories of experimental and production A.R.P. streetlighting fittings, was over 1,200.

5. CONCLUSION.

The need for A.R.P. lighting has brought about a completely new development in illuminating engineering, which has had to take place at high speed. The low levels concerned have brought many new and interesting problems for solution; new kinds of fittings, operating on new principles, have been necessary; and a degree of control in manufacture and installation has had to be established which goes beyond what was usual in peace time. These developments have only been possible as the result of very full co-operation between all the technical interests in the country and much work in their research establishments. The lighting industry will certainly profit in peace time by the new experience and by the collaboration which the war has brought.

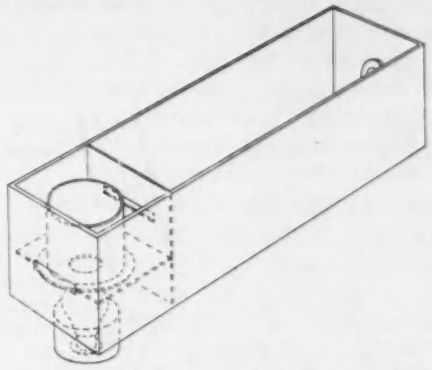

Fig. 20.—Apparatus for routine testing of opal cylinders for street lighting fittings.

Electrical Equipment for Pretoria Trolley Buses.

One of 34 buses with G.E.C. electrical equipment recently supplied to Pretoria City Transport. There are 10 double-deck and 24 single-deck buses, each equipped with an 80 h.p. 500 volt D.C. traction motor and control gear, and arranged for rheostatic braking.

The Design of Fractional Horse-Power Induction Motors.

PART II.

By N. F. T. SAUNDERS, B.Sc.
General Manager, Coldair Ltd., of the G.E.C.

This is the second part of a paper which was read by the author before the Institution of Electrical Engineers in January, 1939. The first part appeared in an earlier issue of the G.E.C. Journal (Vol. X., No. 3, August, 1939).

(14) LEAKAGE REACTANCE.

The calculation of the leakage flux is dealt with in many textbooks,* and from the usual method adopted for slot leakage the following formula for the round-ended slot is derived :—

$$1{\cdot}25\left(0{\cdot}637+\frac{d_3}{3w_3}+\frac{d_2}{w_2}+\frac{d_1}{w_1}\right)=\lambda_s \quad . \quad (16)$$

where the symbols have the meanings indicated in fig. 3. Similarly the rotor slot leakage for the round-ended rectangular case is given by

$$1{\cdot}25\left(1{\cdot}274+\frac{d_5}{3w_5}+\frac{d_4}{w_4}\right)=\lambda_r \quad . \quad . \quad (17)$$

The rotor leakage is referred to the stator by multiplying by the ratio

$$c_\lambda=\frac{\text{Slots occupied by stator winding}}{\text{Number of rotor slots}} \quad . \quad (18)$$

In the single-phase case two values of c_λ are usually required, one being that corresponding to the number of slots occupied by the running winding, and the other corresponding to the number of slots occupied by the starting winding. In the 3-phase case, all the stator slots are usually occupied by windings. Then

$$\lambda_c=\lambda_r\times c_\lambda \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

In the case of a circular-rotor slot this gives

$$\lambda_r=1{\cdot}25\left(0{\cdot}637+\frac{d_6}{w_6}\right) \quad . \quad . \quad . \quad (20)$$

For a closed circular slot, provided the thickness of the bridge is made equal to 18 per cent of the slot diameter, it may be taken that

$$\lambda_r=1{\cdot}25\times 1{\cdot}637. \quad . \quad . \quad . \quad (21)$$

It must be borne in mind, however, that this equation is only reliable when the bridge is saturated, and is liable to errors due to variations in manufacture, as already discussed.

* See, for example, M. G. Say and E. N. Pink: "The Performance and Design of A.C. Machines" (Pitman, 1936), p.163.

A formula† which the author has found to give very good results for the zigzag leakage is

$$\lambda_{zz}=\frac{1{\cdot}25}{6}\times\frac{t^4}{P_1^2P_2g} \quad . \quad (22)$$

For the end winding in the case of concentric or concentric-lap windings the following has been found satisfactory :—

$$\lambda_e=K_d\frac{(\text{Pole pitch}\times 0{\cdot}5P_e)}{(\text{Active core length})}q_1 \quad . \quad (23)$$

where the pole pitch is taken on the gap diameter and where q_1 is the number of slots per pole and phase in the stator. The total leakage is then

$$\lambda=\lambda_s+\lambda_c+\lambda_{zz}+\lambda_e \quad . \quad . \quad . \quad (24)$$

and the reactance in ohms is

$$x_t=12{\cdot}5f\frac{(pq_1z_1)^2\times(\text{Active core length})\times 2{\cdot}54\times\lambda}{pq_1\times 10^8} \quad . \quad . \quad (25)$$

where f is the frequency in cycles per sec.

(15) SHORT-CIRCUIT CURRENT.

The resistance per phase on short-circuit is given by the stator resistance (r_1) plus the rotor resistance referred to the stator (r_2). It is usual to assume that the respective windings will be at the steady full-load temperature (*i.e.* generally 50 deg. C. rise). The total impedance is then

$$Z_t=r_t+jx_t=\sqrt{(r_t^2+x_t^2)} \quad . \quad . \quad (26)$$

and the power factor is given by

$$\cos\phi=\frac{r_t}{\sqrt{(r_t^2+x_t^2)}} \quad . \quad . \quad . \quad . \quad 27)$$

These are the "apparent" impedance and power factor.

In the case of a split-phase motor, care should be taken to calculate the impedance of each winding separately. It is not sufficiently accurate to take the reactance of the starting winding as equal to the

† L. H. A. Carr: *Electrician*, 1921, vol. 87, p. 76.

reactance of the running winding multiplied by the square of the ratio of their respective total conductors. The two windings occupy different proportions of the stator slots, and may not be distributed in the same way.

The value of the short-circuit current calculated in this manner is less than the test value, because the latter includes the magnetizing current. The test value is called the "actual" short-circuit current,

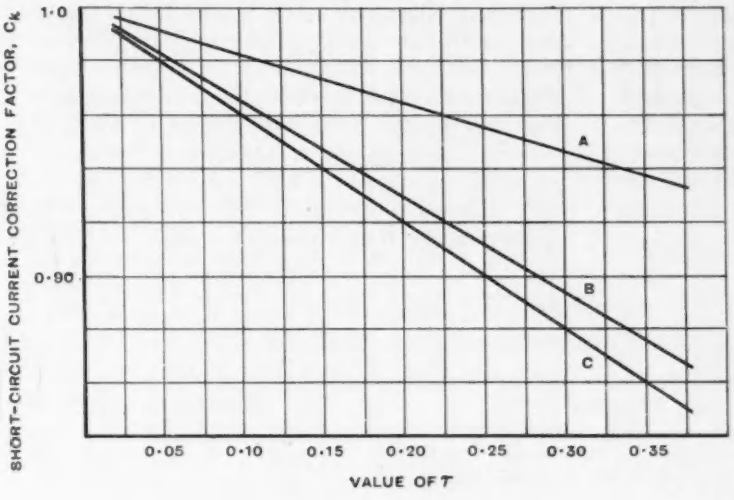

Fig. 6.

A. Polyphase motor, $r_2 = r_1$.
B. Single-phase motor, $r_2 = r_1$.
C. Single-phase motor, $r_2 = 2r_1$.

while the value given by the above is called the "apparent" short-circuit current. Fig. 6 shows the short-circuit current correction factor, namely

$$C_k = \frac{\text{Apparent short-circuit current}}{\text{Actual short-circuit current}} \quad . \quad (28)$$

for different values of $\tau\,(= Z_t/Z_0)$.

Thus, when predetermining the performance of a motor, the actual test figure may be arrived at by using this curve, while, if constants are being established from test data, care must be taken to use this curve to arrive at the "apparent" value before using it to give the impedance and reactance.

It will be noted that separate curves are required for the single-phase and the 3-phase cases. In the 3-phase case, the line current is, of course, $\sqrt{3}$ times the phase current if the stator is mesh-connected, but as it is usual to connect f.h.p. machines in star (in order to reduce the number of conductors per slot) the line current is usually the same as the phase value. The line current taken by the single-phase motor is the vectorial sum of the short-circuit currents in the starting and running windings.

(16) THE MAGNETIC CIRCUIT.

The shape of the slots and teeth has already been dealt with in Section (4). The depth of iron behind the stator slots should be so proportioned that the flux density B_{av} in the core is rather less than the density B_{54} in the teeth. As a guide, it may be taken that suitable densities are 13,000 lines per cm.^{2} for the core and 13,500 lines per cm.^{2} for the teeth. This, of course, means that more ampere-turns will be required for the core than for the teeth, but it is necessary to keep down the tooth density in order to avoid noise and excessive iron loss. The depth of iron below the rotor slots is usually ample, but it should not be disregarded, since in some designs it may be reduced to danger point by ventilation holes, etc. If holes are required in the stator core for rivets, each should be placed in line with a tooth. Provided the holes are not larger in diameter than the width of the tooth, they may be disregarded. In order to avoid losses due to circulating currents, these rivets should be placed as near as is mechanically sound to the periphery, and the single-phase stator should be wound so that the rivet lies on the pole centre-line.

With the shape of slot recommended, the effective depth of the iron behind the slots may be taken as the minimum plus 20 per cent of the radius at the bottom of the slot. In calculating the actual sections of the various paths in the magnetic circuit, it is important to allow for the insulation between the laminations. The type of insulating material which is very popular in f.h.p. machines has a china-clay base and is sprayed on to the steel sheets. The adhesion is so good that the sheets may be stamped out after insulating. For laminations 0·018in. thick (a popular thickness in this class of work), the active core-length may be taken as 90 per cent of the actual core-length. If, however, the laminations are annealed after stamping, the film of oxide which appears forms an effective insulation and the factor may be taken as 93 per cent.

(17) THE FLUX CALCULATION.

The flux per pole is given by the expression

$$\Phi = \frac{E_p \times 10^8}{2{\cdot}22\, K_d K_f f(2pq_1)z_1} \quad . \quad . \quad . \quad (29)$$

where E_p is the e.m.f. per phase and allows for the stator impedance drop. In the case of f.h.p. machines, the no-load power factor is usually of the order of 0·2 and the full-load power factor of the order of

0·70 to 0·75. Assuming these values, and that $r_1 = x_1$, the error is not very considerable if it is taken that

$$\text{On no load, } E_p = V_p - I_0 r_1 \quad . \quad . \quad (30)$$

$$\text{On full load, } E_p = V_p - I_0 Z_1 \quad . \quad . \quad (31)$$

where V_p is the applied voltage per phase.

Or, alternatively,

$$\text{On full load, } E_p = V_p - \sqrt{2} I_1 r_1 \quad . \quad (32)$$

where in each case the drop is subtracted arithmetically. This allowance for the stator drop represents one of the most important differences between large- and small-machine design. The assumption which is usually made in large-machine design that the magnetizing current is constant, is not justifiable here.

When calculating the general performance figures of a proposed design, the flux must be deduced from the e.m.f. corresponding to the load in question. If, after a winding has been established, it is found that the preliminary assumption of equality of resistance and reactance is appreciably in error, a revised calculation should be made, using the correct value of E_p. An important consideration is that the difference in the e.m.f. between full load and no load generally produces a marked difference in the iron loss. The result is that if the full-load efficiency is calculated by the summation-of-losses (including stray loss) method laid down in British Standard Specification No. 269—1927, the result is pessimistic. For this reason it is recommended that f.h.p. motors should be tested against a brake. For example, on a $\frac{1}{4}$ h.p. 1,400-r.p.m. split-phase motor the difference between the efficiency values established by the two methods might be 2 points.

TABLE 4.

SINGLE-PHASE INDUCTION MOTOR.

	Practical.	Theoretical.
Primary current at slip s	$\dfrac{\text{Input watts}}{\text{Applied volts} \times \text{p.f.}} = \dfrac{P}{V_1 \cos F\phi}$	$V_1 \sqrt{\left[\dfrac{(s_0 r_m + 2r_2)^2 + (s_0 x_m + 2s x_2)^2}{(\gamma - s\beta + s_0\varepsilon)^2 + (\chi + s\psi + s_0\omega)^2}\right]}$
Power output at slip s	Input minus losses	$\dfrac{s_0(1-s)^2 V_1^2 Z_m^2 r_2}{(\gamma - s\beta + s_0\varepsilon)^2 + (\chi + s\psi + s_0\omega)^2}$
Torque at slip s	Power $\times \dfrac{1}{1-s}$	$\dfrac{s_0(1-s) V_1^2 Z_m^2 r_2}{(\gamma - s\beta + s_0\varepsilon)^2 + (\chi + s\psi + s_0\omega)^2}$
Slip at max. power output, s_P	$\dfrac{r_2}{2Z_t + r_2}$	
Max. output (horse-power), P_m	$\dfrac{s_{0P}(1 - s_{0P}) V_1^2 C_P}{r_2\left(1 + 0{\cdot}68\tau + s_{0P}\dfrac{r_1}{r_2}\right)^2 \times 746}$	From power/slip curve
Slip at max. torque, s_T	$\dfrac{r_2}{Z_t + x_t}$	
Max. torque (synchronous watts), T_m ...	$\dfrac{s_{0T}(1 - s_T)\ V_1^2 \times 0{\cdot}86}{r_2\left(1 + 0{\cdot}68\tau + s_{0T}\dfrac{r_1}{r_2}\right)^2}$	From torque/slip curve
Power factor	From curves	$\dfrac{(s_0 r_m + 2r_2)(\gamma - s\beta + s_0\varepsilon) + (s_0 x_m + 2s x_2)(\chi + s\psi + s_0\omega)}{\sqrt{\left[\left\{(s_0 r_m + 2r_2)(\gamma - s\beta + s_0\varepsilon) + (s_0 x_m + 2s x_2)(\chi + s\psi + s_0\omega)\right\}^2 + \left\{s_0 x_m + 2s x_2)(\gamma - s\beta + s_0\varepsilon) - (s_0 r_m + 2r_2)(\chi + s\psi + s_0\omega)\right\}^2\right]}}$
Actual short-circuit current (I_k)	$V_1/(Z_t C_k)$	
Actual short-circuit power factor ($\cos \phi_k$)	$r_t C\phi / Z_t$	
Starting torque	$2 I'_{Rk} K_T I'_{Sk} \sin\theta r_2$	

I'_{Rk} = apparent short-circuit current in running winding; I'_{Sk} = apparent short-circuit current in starting winding; K_T = ratio of transformation between the two windings; s = slip; $n = (1-s)$ = speed; $s_0 = 1 - n^2$; $Z_1 = r_1 + jx_1$ = primary self-inductive impedance; $Z_2 = r_2 + jx_2$ = secondary self-inductive impedance; $Z_m = r_m + jx_m$ = mutual inductive impedance; $Z_t = r_t + jx_t = Z_1 + Z_2$; $\beta = x_2(x_m + 2x_1)$; $\gamma = r_2(r_m + 2r_1)$; $\varepsilon = (r_m r_1 - x_m x_1)$; $\theta = \phi'_{Rk} - \phi'_{Sk}$, where $\cos \phi'_{Rk}$ and $\cos \phi'_{Sk}$ are apparent values; $\chi = r_2(x_m + 2x_1)$; $\psi = x_2(r_m + 2r_1)$; $\omega = (r_m x_1 + x_m r_1)$.

(18) THE MAGNETIZING CURRENT.

The flux through the core is taken as the value established by equation (29). For the stator and rotor teeth, the value is taken as 1·28 times the core

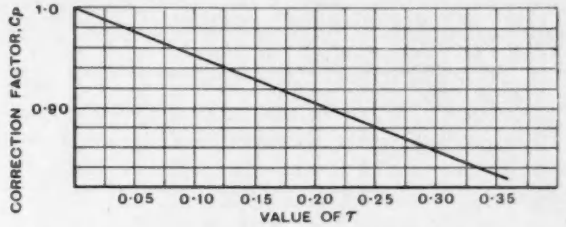

Fig. 7.—Polyphase motor: maximum horse-power correction factor.

$$\text{Maximum horse-power} = \frac{3C_P V_{ph}^2}{2(Z_t + r_t)\,0.746}$$

value. This value is, however, reduced by 5 per cent to 7½ per cent in its passage through the stator teeth, and by a similar amount in its passage through the rotor teeth.

A magnetization curve is obtainable from the manufacturer of the grade of steel it is proposed to use. When choosing the type of steel, it is very important to consider the iron-loss curve as well as the magnetization curve. It is generally found that a low-loss iron has a low permeability. Careful consideration will show that, generally, permeability is of more consequence than iron loss, since the copper loss due to the magnetizing current may well exceed the iron loss. This is the more likely the smaller the machine or the smaller the power required.

The magnetizing current is found from the total ampere-turns ($\Sigma\bar{A}$) as follows:—

$$\text{Three-phase magnetizing current} = \frac{\Sigma\bar{A}}{2{\cdot}22K_dK_cq_1z_1} \quad (33)$$

Single-phase magnetizing current

$$= \frac{\Sigma\bar{A}}{1{\cdot}54K_dK_cq_1z_1} \times \frac{2+2\sigma}{1+2\sigma} \quad . \; . \quad (34)$$

where σ is the flux loss through the teeth (amounting to 10 per cent to 15 per cent).

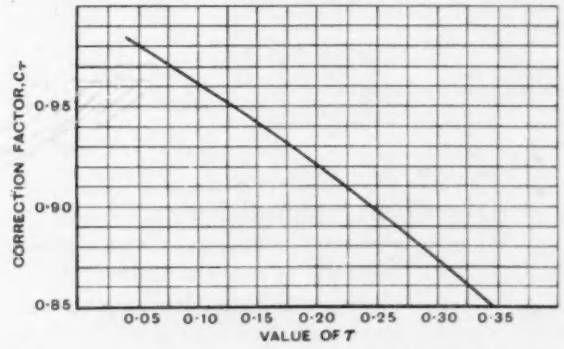

Fig. 8.—Polyphase motor: maximum torque correction factor.

$$\text{Maximum torque} = \frac{3C_T\,V_{ph}^2}{2[r_1 + \sqrt{(r_1^2 + x_0^2)}]}$$

(19) IRON LOSSES.

On the assumption that working dimensions are expressed in inches, it is convenient to calculate the volume of iron in the stator core and teeth in cubic inches, and then to use curves giving the watts loss per cubic inch at the frequency in question. The total iron loss may be taken as

$$p_i = (\text{Core volume}) \times (\text{Loss per cu. in.}) + 3\,(\text{Tooth volume}) \times (\text{Loss per cu. in.}) \quad (35)$$

In each case the loss per cubic inch must be based on the maximum flux density. This value is then, for the core, the average density used to establish the ampere-turns multiplied by 1·59; and, for the teeth, the B_{54} value used in the magnetization table multiplied by 1·24. As has been stated before, care must be taken, when calculating a load performance, to take the magnetizing current and iron loss

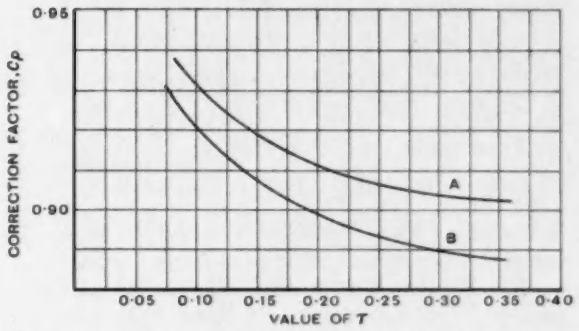

Fig. 9.—Single-phase motor: maximum horse-power correction factor.

A. $r_2 = r_1$.
B. $r_2 = 2r_1$.

at that load. Taking the iron loss at full load, an equivalent current and impedance Z_0 may be established as follows:—

$$\text{On single-phase, } I_i = \frac{P_i}{V} \quad . \; . \quad (36)$$

$$\text{On 3-phase, } \quad I_i = \frac{P_i}{\sqrt{3}V} \quad . \; . \quad (37)$$

An equivalent total "loss" current is then

$$I_0 = \sqrt{(I_i^2 + I_m^2)} \quad . \; . \; . \; . \quad (38)$$

where I_m is the magnetizing current at full load. Then

$$Z_0 = \frac{V_p}{I_0} \quad . \; . \; . \; . \; . \quad (39)$$

The important operator τ is given by the ratio

$$\tau = \frac{Z_i}{Z_0} \quad . \; . \; . \; . \; . \; . \quad (40)$$

If it is desired to predetermine the no-load current, it may be found in the same way, using no-load values of iron loss and magnetizing current.

(20) CORRECTION FACTORS.

Table 4 gives, for the single-phase case, the method or formulae recommended for obtaining the various performance data. In the adjoining column the correct formulae are given, except in some cases where the complication is excessive. It will be noted that, in the practical column, correction factors appear. These are arrived at by calculating the correct values by means of the formulae in the second column, using nominal values for the various impedances, and for a series of values of τ. The 3-phase formulae have previously been given in a convenient form by Hoseason,* while the method by which the single-phase formulae are obtained is described in the Appendix.

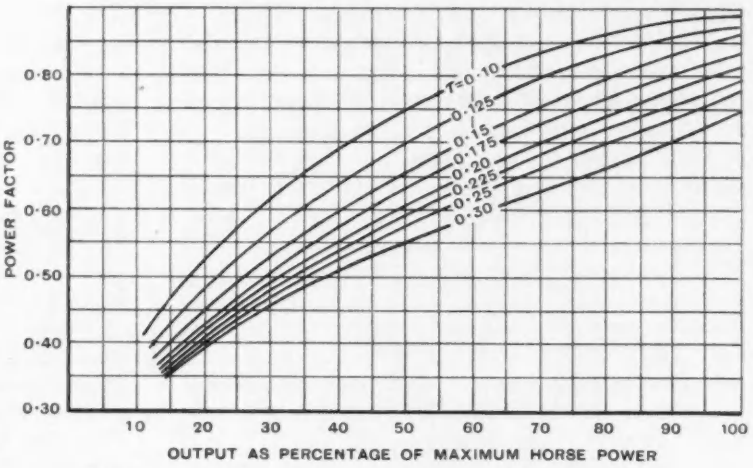

Fig. 11.—Single-phase motor: characteristics based on $\cos\phi_0 = 0.20$, $\cos\phi_k = 0.75$, $r_2 = r_1$.

It is found that, in f.h.p. machines, average values for the "loss" current power factor, and the short-circuit power factor, are

Three-phase $\cos\phi_t = 0{\cdot}75$, $\cos\phi_0 = 0{\cdot}15$

Single-phase $\cos\phi_t = 0{\cdot}75$, $\cos\phi_0 = 0{\cdot}20$

These values have been used to establish the various correction factors and the power-factor curves.

Fig. 7 gives the correction factor for maximum horse-power (C_P) and fig. 8 gives the factor for maximum torque (C_T) in the polyphase case. Fig. 9 gives the correction factor for maximum horse-power in the single-phase case; a close degree of accuracy is attained if the maximum-torque correction factor in the single-phase case is taken as the constant value 0·86.

* *Journal I.E.E.*, 1925, vol. 63, p.280.

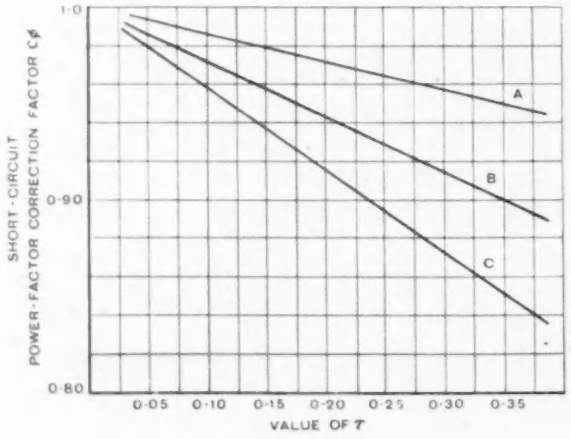

Fig. 10.

A. Polyphase motor, $r_2 = r_1$.
B. Single-phase motor, $r_2 = r_1$.
C. Single-phase motor, $r_2 = 2r_1$.

The actual (test) value of the short-circuit power factor is lower than the apparent power factor and is given by

$$\cos\phi_k = \left(\frac{r_t}{z_t} \times C\phi\right) \quad . \; . \; . \quad (41)$$

Fig. 10 gives the correction factors for both polyphase and single-phase cases.

In calculating the polyphase maximum horse-power and torque for practical design purposes, the usual simplified formulae are used in conjunction with the above correction factors. In the single-phase case, however, the method adopted is that of calculating first the slip at which these maxima occur and then using these slip values in calculating the maximum horse-power and torque. It will be noted that in the polyphase case it is assumed that $r_2 = r_1$, but in the single-phase case the ratio of these two values appears, so that accuracy is possible over a wide variation in this ratio.

(21) STARTING TORQUE OF SPLIT-PHASE MOTOR.

The starting torque of the split-phase motor is given by

$$T_k = 2I'_{RK}K_T I'_{SK}\sin\theta \,.\, r_2 \quad . \; . \; . \quad (42)$$

where I'_{RK} = apparent short-circuit current in running winding,

I'_{SK} = apparent short-circuit current in starting winding,

θ = angle between these two currents,

r_2 = rotor resistance referred to running winding,

Also K_T = ratio of transformation between the two windings

$$= \frac{K_d \times \text{Conductors in starting winding}}{K'_d \times \text{Conductor in running winding}} \quad . \; . \quad (43)$$

where K_d, K'_d are the distribution factors for the starting and running windings respectively.

The full-load torque in synchronous watts is given by

$$\frac{\text{Horse-power} \times 746}{1 - s} \quad . \quad . \quad . \quad (44)$$

where s is the slip at full load.

It is usual to equate the two in order to give the starting torque as a percentage of full-load torque.

There is no necessity to complicate the expression by substituting for sin θ. It is convenient to find the angles corresponding to $\cos \phi'_{RK}$ and $\cos \phi'_{SK}$, deduce θ by subtraction, and then find sin θ from trigonometrical tables. The angle θ may be established in a variety of ways, but the majority of practical requirements in f.h.p. motors are met either by adding resistance to the starting winding or by connecting a condenser in series with it. The former is what is generally understood by the term "split-phase" motor, while the latter is called a "capacitor-start" motor.

In the split-phase motor, the starting winding usually occupies about half as many slots as the running winding, and has approximately the same number of conductors per coil, so that the total number of conductors in the starting winding is approximately half the number in the running winding. The section of the conductors is reduced to something of the order of 20 per cent of the section of the running-winding conductors in order to give the required increased resistance using copper wire. Such a winding is of course only suitable provided it is in circuit only a very short time. In practice a centrifugal switch is generally used which cuts out the starting winding as soon as the motor has reached about 80 per cent of synchronous speed. Under these conditions, the current density at starting may be as high as 60,000 amp. per sq. in. A more robust machine is obtained by using a resistance external to the winding. This may take the form of nichrome wire or tape, wound on mica sheets. This arrangement is, however, becoming obsolete, owing to the extremely low prices ruling for split-phase motors.

The capacitor-start motor is rapidly becoming very popular, mainly because it can be designed to give a very high starting torque for a reasonable starting current. The starting condenser is usually of the electrolytic type which has been developed for this machine. These condensers are very reliable and compact. As a guide, it may be taken that the usual size for a 230-volts 50-cycle ¼ h.p. motor is 30 μF. The condenser, which gives a high starting torque, is too large to be left in circuit when the motor is running. Also, of course, the electrolytic type is only suitable for intermittent duty and must be cut out as soon as the motor is up to speed. In this country it is quite common to use a magnetic switch to open-circuit the starting winding and condenser, but provided the design is good a centrifugal switch is satisfactory and much cheaper. If it is desired to leave a small condenser permanently in circuit in order to obtain a modified 2-phase motor on load, this permanent condenser must be of the paper type. In this case the switch is used to open-circuit the starting condenser only. A large variety of forms of the capacitor-start and run motor has appeared, but at the present time attention is almost entirely confined to the straightforward capacitor-start motor. For drives such as fans where the required starting torque is low, a small single condenser is connected permanently in circuit.

The formula given in this paper for the starting torque of the single-phase motor may be used in the capacitor-start case.

(22) CALCULATION OF PERFORMANCE ON LOAD.

The efficiency on load may be calculated to a close degree of accuracy, provided the iron loss is based on the actual flux at the load in question, and provided information is available regarding the friction loss in the bearings and the energy required to drive the fan, if one is fitted. Owing to the large variety in fan and bearing designs, it is difficult to give figures for these items, but, as a guide, it may be

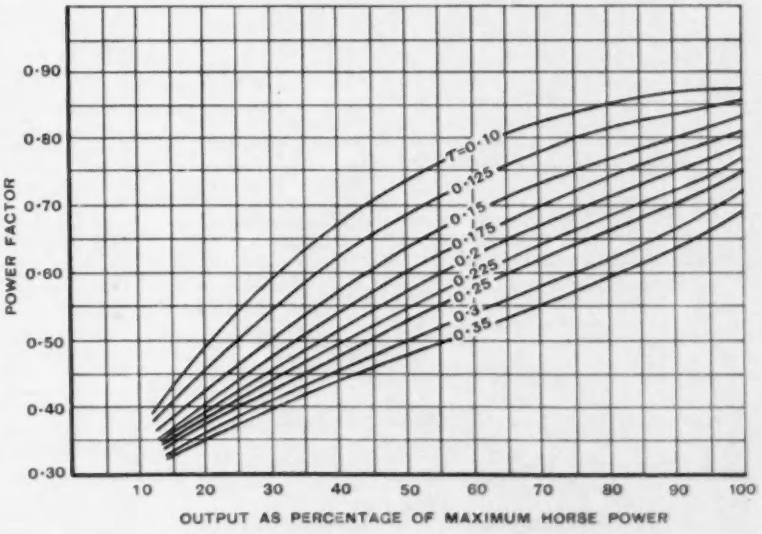

Fig. 12.—Single-phase motor: characteristics based on $\cos \phi_0 = 0.20$, $\cos \phi_k = 0.75$, $r_2 = 2r_1$.

taken that for a machine with ball bearings the friction and windage loss at 1,400 r.p.m. should not exceed 7½ per cent of the full-load output. For a machine with sleeve bearings of good design, this loss should not exceed 10 per cent.

In the single-phase case, the slip at maximum horse-power is first calculated, and from this the maximum horse-power is obtained. Using the value of τ already determined, the power factor at any load follows from the curves of figs. 11 or 12, whichever is applicable. In the 3-phase case the maximum horse-power is calculated in the usual manner, and then the power factor follows from the curves given in fig. 13. The primary current is arrived at by a process of trial and error in the usual manner, since the stator copper loss depends on the current assumed. Incidentally, the calculation of the slip at maximum horse-power in the single-phase case is useful in establishing the speed at which the centrifugal switch should operate.

For ordinary use, and since the designer of f.h.p. machines is generally called on to produce a large number of designs and has very little time to spend on each, the two types of design sheets reproduced in Tables 5 and 6 are recommended. Both sheets are used in the case of an original design, and they then record the complete data for the machine. Obviously, once a number of machines have passed through their tests, it is useful to go back and correct the original design if the average test figures depart materially from it. When, however, a modification of an existing design will meet the case, the first sheet (Table 5) only is often sufficient, or in some cases part only of the second sheet may be used. Once a design has been established, it is usually required for various voltages and frequencies, in which case it is useful to use simple winding record

TABLE 5.

INDUCTION MOTOR DESIGN SHEET ORDER NO. _____

_____ PHASE MOTOR TYPE _____ CUSTOMER _____

_____ B.H.P. _____ VOLTS _____~_____ POLES _____ R.P.M. (SYN.) _____ FL

| | | |

sheets which are filed with the corresponding complete design sheet. Windings for various voltages and frequencies are quickly established from the formula

$$T_R = T_S \times \frac{V_R}{V_S}\sqrt{\left(\frac{\text{Standard h.p.}}{\text{Required h.p.}} \times \frac{f_S}{f_R}\right)} \quad (45)$$

where the subscripts R and S stand for "required" and "standard" respectively. It is strongly recommended that the design sheets be used whenever applicable, even though at the time only a few figures can be filled in.

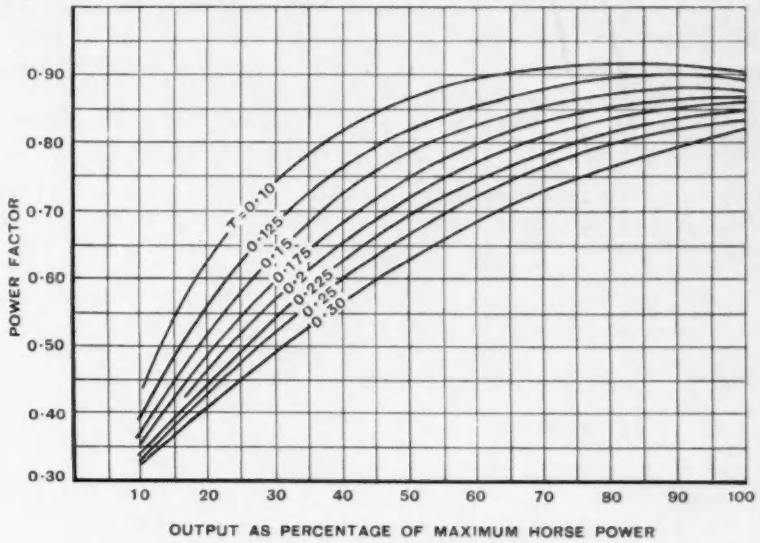

Fig. 13.—Polyphase motor: characteristics based on $\cos\phi_3 = 0.15$, $\cos\phi_R = 0.75$, $r_2 = r_1$.

(23) ACKNOWLEDGMENTS.

The author is indebted to Mr. D. B. Hoseason, M.I.E.E., for much helpful advice and criticism, particularly in connection with the calculation of the curves reproduced in fig. 13, also to Miss D. Smith, A.M.I.E.E., for checking various calculations.

Much assistance in checking formulae was derived from test figures supplied by Lancashire Dynamo and Crypto, Ltd.

APPENDIX.

Derivation of Single-Phase Performance Formulae.

The following notation is employed in this Appendix :—

I_1 = primary current ;
n = speed $= 1 - s$;
$s_0 = 1 - n^2$;
V_1 = applied voltage ;
$Z_m = r_m + jx_m$ = mutual inductive impedance ;
$Z_1 = r_1 + jx_1$ = primary self-inductive impedance;
$Z_2 = r_2 + jx_2$ = secondary self-inductive impedance ;
$Z_t = r_t + jx_t = Z_1 + Z_2$.

It was shown by Steinmetz* that, neglecting quantities of the second order, the primary current is given by

$$I_1 = \frac{V_1[Z_m s_0 + 2Z_2]}{Z_m(Z_1 s_0 + Z_2) + 2Z_1 Z_2}$$

The numerator of this expression, when expanded, becomes

$$V_1[(s_0 r_m + 2r_2) + j(s_0 x_m + 2sx_2)]$$

The denominator becomes

$$r_2(r_m + 2r_1) + s_0(r_m r_1 - x_m x_1) - sx_2(x_m + 2x_1) + j[r_2(x_m + 2x_1) + sx_2(r_m + 2r_1) + s_0(r_m x_1 + x_m r_1)]$$

The expression then takes the form

$$I_1 = V_1 \frac{(s_0 r_m + 2r_2) + j(s_0 x_m + 2sx_2)}{(\gamma - s\rho + s_0\varepsilon) + j(\chi + s\psi + s_0\omega)}$$

Where

$\gamma = r_2(r_m + 2r_1)$, $\chi = r_2(x_m + 2x_1)$,
$\rho = x_2(x_m + 2x_1)$, $\psi = x_2(r_m + 2r_1)$,
$\varepsilon = (r_m r_1 - x_m x_1)$, $\omega = (r_m x_1 + x_m r_1)$.

When rationalized the numerator becomes

$$V_1\{[(s_0 r_m + 2r_2)(\gamma - s\rho + s_0\varepsilon) + (s_0 x_m + sx_2)(\chi + s\psi + s_0\omega)] + j[(s_0 x_m + sx_2)(\gamma - s\rho + s_0\varepsilon) - (s_0 r_m + 2r_2)(\chi + s\psi + s_0\omega)]\}$$

The denominator becomes

$$(\gamma - s\rho + s_0\varepsilon)^2 + (\chi + s\psi + s_0\omega)^2$$

But V_1 and the denominator are scalar, and therefore the power factor $\cos\phi$ is given by

$$\cos\phi = \frac{x}{\sqrt{(x^2 + y^2)}}$$

* "Theory and Calculation of Electrical Apparatus," p. 317.

where

$$x=(s_0r_m+2r_2)(\gamma-s\rho+s_0\varepsilon)+(s_0x_m+2sx_2)(\chi+s\psi+s_0\omega)$$

$$y=(s_0x_m+2sx_2)(\gamma-s\rho+s_0\varepsilon)-(s_0r_m+2r_2)(\chi+s\psi+s_0\omega)$$

The primary current is

$$I_1=V_1\sqrt{\left[\frac{(s_0r_m+2r_2)^2+(s_0x_m+2sx_2)}{(\gamma-s\rho+s_0\varepsilon)^2+(\chi+s\psi+s_0\omega)^2}\right]}$$

Similarly the power output at slip s is

$$P=\frac{s_0(1-s)^2V_1^2Z_m^2r_2}{(\gamma-s\rho+s_0\varepsilon)^2+(\chi+s\psi+s_0\omega)^2}$$

and the torque at slip s is

$$T=\frac{s_0(1-s)V_1^2Z_m^2r_2}{(\gamma-s\rho+s_0\varepsilon)^2+(\chi+s\psi+s_0\omega)^2}$$

A simplified expression for the maximum power output, for practical use, is obtained as follows :—

The maximum power is given by

$$P_{max.}=\frac{s_{0P}(1-s_P)^2V_1^2Z_m^2r_2}{(\gamma-s_P\rho+s_{0P}\varepsilon)^2+(\chi+s_P\psi+s_{0P}\omega)^2}$$

where s_P and s_{0P} are the values of s and s_0 corresponding to maximum power.

By differentiating the above expression it is shown that

$$s_P=\frac{r_2}{2Z_t+r_2}$$

At maximum power, however, it is possible to neglect $(\gamma-s_P\rho+s_{0P}\varepsilon)$ and also $s_P\psi$. In the equation

$$\omega=(r_mx_1+x_mr_1)$$

the part r_mx_1 may also be neglected. The expression for the maximum power output then becomes

$$P_{max.}=\frac{s_{0P}(1-s_P)^2V_1^2Z_m^2r_2}{(r_2x_m+2r_2x_1+s_{0P}x_mr_1)^2}$$

$$=\frac{s_{0P}(1-s_P)^2V_1^2Z_m^2r^2}{r_2^2x_m^2\left(1+2\frac{x_1}{x_m}+s_{0P}\frac{r_1}{r_2}\right)^2}$$

Taking now $Z_m=x_m$ (approximately), and assuming that $\cos\phi_0=0{\cdot}2$ and $\cos\phi_k=0{\cdot}75$, we have

$$P_{max.}=\frac{s_{0P}(1-s_P)^2V_1^2}{r_2\left(1+0{\cdot}68\tau+s_{0P}\frac{r_1}{r_2}\right)^2}$$

$$=\frac{s_{0P}(1-s_{0P})V_1^2}{r_2\left(1+0{\cdot}68\tau+s_{0P}\frac{r_1}{r_2}\right)^2}$$

Similarly a simplified expression is found for $T_{max.}$

By taking nominal values for the various impedances for various values of τ the power factor may be calculated for successive values of s, thus establishing the curves given in figs. 11, 12, and 13. In the same way the power output at each slip value may be determined, and by plotting these values on a curve the maximum power is obtained. Thus the various power values may be expressed as a percentage of the maximum. Also, by calculating for each value of τ the maximum power from the approximate formula

$$P_{max.}=\frac{s_{0P}(1-s_P)^2V_1^2}{r_2\left(1+0{\cdot}68\tau+s_{0P}\frac{r_1}{r_2}\right)^2}$$

and equating the results to the corresponding maximum values using the more correct expression, the correction factor C_P is obtained.

From the values established in calculating the power-factor curves extended to $s=1$ the primary current is arrived at, and then by equating to the values given by the formula $I_k'=V_1/Z_t$ the correction-factor curve (fig. 6) is obtained. Curves A and B in fig. 6 are based on the assumption that the secondary and primary resistances are equal, while for Curve C the assumption is that the secondary resistance is twice the primary. The latter is generally the case to a close approximation where starting is effected by means of resistance in the starting phase (the ordinary split-phase motor). When the machine is of the capacitor-start type it is often possible to make the secondary resistance as low as the primary. In any event it is clear that for intermediate cases it is possible to interpolate between the two sets of curves.

In both cases the assumption is made that $x_1=x_2$. Again from the values calculated for $s=1$ the actual short-circuit power factor is obtained, and by equating this to the "apparent" value where

$$\cos\phi_k\text{ (apparent)}=\frac{r_t}{r_t+jx_t}$$

the $C\phi$ correction-factor curves are obtained.

The Micro-Analysis of Gases by Physical Methods.

By C. E. RANSLEY, M.Sc., Ph.D.
G.E.C. Research Laboratories, Wembley, England.

The author reviews the methods which are available for the quantitative analysis of very small volumes of gas. He describes an apparatus for the micro-analysis of gas mixtures at low pressures, in which physical tests are used as far as possible for identification of the various gases.

In certain analytical operations the low pressure method possesses definite advantages over ordinary chemical procedure.

INTRODUCTION.

IN recent years a considerable amount of work has been done in the Research Laboratories on the degassing of metals, the diffusion of gases through metals, and similar problems bearing on the selection and treatment of the various materials used in vacuum devices. In such work it is essential to have available some means of analysing the very small quantities of gas which must be handled. In thermionic valves, for example, certain gases have a more deleterious effect than others, and in assessing the "gassing" properties of the materials used for electrodes, it is often more important to know the composition than the volume of the gas evolved. This is also true of diffusion experiments; many workers have drawn erroneous conclusions as to the rate of diffusion of compound gases through metals by omitting to analyse the gas collected on the vacuum side of the diffusion diaphragm. It is surprising how often this turns out to be hydrogen, which may be present as an impurity in the gas under investigation, or perhaps be derived from a side-reaction at the gas-metal interface. In comparison with other gases, hydrogen diffuses very rapidly through most metals, and a mere trace is sufficient to give a high apparent rate of diffusion.

Analytical results can be of direct practical assistance in a number of ways, *e.g.*, an analysis of the minute amounts of gas which collect in certain vacuum devices under service conditions will often enable the source of the gas to be determined, and the trouble rectified.

Since the total volume of gas available for analysis in work of this kind may amount to only about 0·001 c.c. measured at S.T.P., it is obvious that ordinary chemical procedure cannot be used. The minimum volume that can be quantitatively analysed by normal macro-methods is probably about 10 c.c., although smaller volumes down to about 1 c.c. can be dealt with when special precautions are taken. The methods available for the analysis of much smaller samples may be broadly classified into two groups, *i.e.*, those in which the gas is manipulated at approximately atmospheric pressure, and those in which the analysis is carried out at very reduced pressures. The first group comprises what may be termed purely chemical methods; generally speaking these involve the use of capillary burettes, and solid reagents or impregnated beads are used for the removal of the various gases. Several ingenious techniques have been developed on these lines, and it is possible to carry out analyses on samples as small as 0·1 c.c. with an accuracy comparable with that normally attained in macro-analysis using 100 c.c. of gas.[1] It is not possible, however, to extend the sensitivity much below this figure, and for our purpose it is necessary to turn to low pressure methods, following the technique first introduced by I. Langmuir[2] in his investigations on gaseous reactions at solid surfaces.

In micro-analysis at low pressures, the gas mixture is confined in a fixed volume, and the constituent gases are identified and measured by a succession of chemical or physical processes. Pressure changes in the system are followed by means of a McLeod or other sensitive vacuum gauge. This article describes an apparatus and scheme for such analysis, which have been developed during the work on gases and metals mentioned above. The procedure is considered to be relatively simple in operation, and the accuracy is well within the limits normally required in such work. As far as possible, use has been made of physical methods of identification, since these are to be preferred when working under vacuum conditions. One definite advantage is that the analysis is to a certain extent reversible, so that any number of repeat measurements can be made on one particular sample.

The sensitivity of the low pressure method is due to the fact that there are gauges available for measuring pressures accurately down to 10^{-5} mm. of mercury, or less, and since the volume of the analytical

system may be varied within wide limits, it is possible to determine quite accurately the mass (or volume at S.T.P.) of very small amounts of gas. For this reason, the low pressure technique has definite advantages in certain analytical operations, *e.g.*, the determination of oxygen and carbon in metals, in which ordinary chemical procedure, depending as it does upon the weighing of small increments, involves obvious difficulties. Another application, of which an example will be given later, is the determination of minor constituents in normal-sized gas samples. In favourable cases, these may be determined very simply by the low pressure technique.

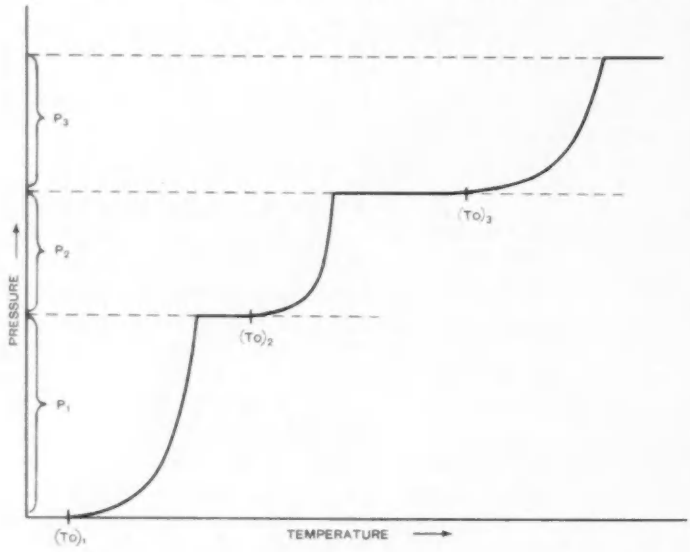

Fig. 1.—Ideal vapour-pressure curve for a mixture of gases.

METHODS FOR LOW PRESSURE GAS ANALYSIS.

H. M. Ryder[3] has described a method for the analysis of mixtures containing water vapour, CO_2, CO, H_2, CH_4 and N_2, in which the water vapour and CO_2 are differentiated by freezing out with appropriate agents. CO and H_2 are burned with excess oxygen at a platinum filament and determined as water vapour and CO_2. An accuracy of approximately 5 per cent is quoted, for a sample of about 0·005 c.c. Another method to which reference may be made is that due to C. H. Prescott,[4] who gives a procedure for the analysis of mixtures containing H_2, CO, CO_2 and N_2. The CO_2 is absorbed by soda-lime, and the H_2 and CO oxidised by passage over heated copper oxide ; the water vapour formed is then absorbed in P_2O_5. In these methods, pressure changes are measured by means of the McLeod gauge ; Ryder in addition measures the pressure of water vapour in a limited volume using an optical lever mercury gauge.

In the procedure to be described it has been found convenient to divide the sample into two fractions, which are analysed separately. These fractions consist of (*a*) condensable gases or vapours such as CO_2, SO_2 and H_2O, which are determined by means of differential evaporation, or by the use of suitable freezing agents, and (*b*) "permanent gases" (*e.g.*, H_2, O_2, CO, N_2, Ar), which it is desired to identify as far as possible by means of physical tests.

The methods available for the determination of the separate gases will be considered in greater detail.

THE ANALYSIS OF VAPOURS.

The identification of condensable gases by the method of low temperature distillation, using the Pirani pressure gauge, was first introduced by N. R. Campbell.[5] This method depends upon the fact that the vapour pressure of any substance may be represented by Clapeyron equation

$$\frac{d(\log P)}{dT} = \frac{L}{RT^2}$$

where P is the pressure, T is the absolute temperature, and L is the heat of vaporization. The vapour pressure is thus an exponential function of the temperature, and in many cases rises from an unmeasurable value (*i.e.*, less than 10^{-5} mm. for our present purpose) to 0·1 mm. over a very narrow temperature range. Approximate vapour pressures of a few of the commoner gases are given in Table 1.

TABLE 1.

Vapour Pressure of Gases.

Gas	Temperature (°C.) for various vapour pressures (mm. of mercury)				
	10^{-3}	10^{-4}	10^{-3}	10^{-2}	10^{-1}
H_2O ..	– 99	– 88	– 74	– 58	– 39
CO_2 ..	–182	–175	–167	–158	–149
SO_2 ..	–153	–144	–135	–124	–112
NH_3 ..	–164	–156	–148	–137	–124

A gas may thus be said to have a well-defined "condensation temperature" T_0, approaching which the vapour pressure rapidly tends to zero when referred to a certain sensitivity gauge. If we assume that the pressure gauge used can be read accurately down to 1×10^{-4} mm. or perhaps 5×10^{-5} mm., then the characteristic T_0 for CO_2 is –178°C., and for water vapour –90°C.

Suppose, then, that we have a sample of gas consisting of a mixture of several different vapours, contained in an analytical system at a total pressure of say 0·03 mm. If a small side tube attached to the system is cooled with a suitable refrigerant so that all the vapours are condensed out, and is then

allowed to heat up again at a uniform rate, a pressure–temperature curve of the type shown in fig. 1 should be observed.

Here $(T_0)_1$, $(T_0)_2$, $(T_0)_3$ indicate the condensation temperatures of the vapours present, and P_1, P_2, P_3 their respective partial pressures. It will be seen, therefore, that if the vapours present are such that the first one attains its full partial pressure before the temperature of the side tube rises to the condensation temperature of the second, and so on, it will be possible to determine the composition of the sample from such a vapour pressure–temperature curve.

If the condensation temperatures are not too close to one another, and other complications such as the formation of solid solutions do not arise, this method works well in practice. If the constituents of the sample are known, differentiation between them may be made by immersing a side tube in various freezing agents and observing the resultant drop in pressure. Freezing acetone (–95°C.), for example, will freeze out water vapour but not CO_2, and liquid air (–183°C.) will freeze out CO_2 but not the permanent gases. Other useful refrigerants* are freezing chloroform (–65°C.), trichlorethylene (–86°C.) and ethyl alcohol (–117°C.); they are readily prepared by gently adding liquid air to the liquid contained in a small vacuum flask, until the solid separates out.

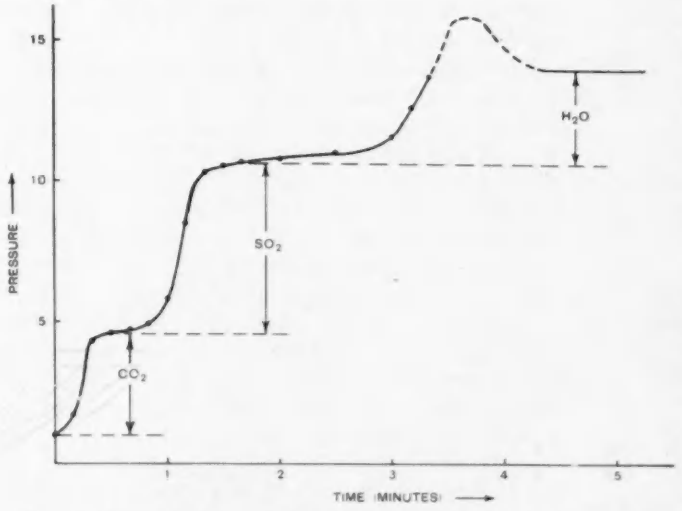

Fig. 2.—Vapour-pressure curve for a standard CO_2—SO_2 mixture.

It is not always easy, however, to obtain a suitable refrigerant to condense a particular vapour, and a more useful general method is to determine the temperature–vapour–pressure curve as referred to above. A simple method of carrying this out is to immerse the side tube in a small vacuum flask containing a little mercury; liquid air is then poured into the flask until the mercury is thoroughly cooled, and some excess liquid air is present. A gentle blast

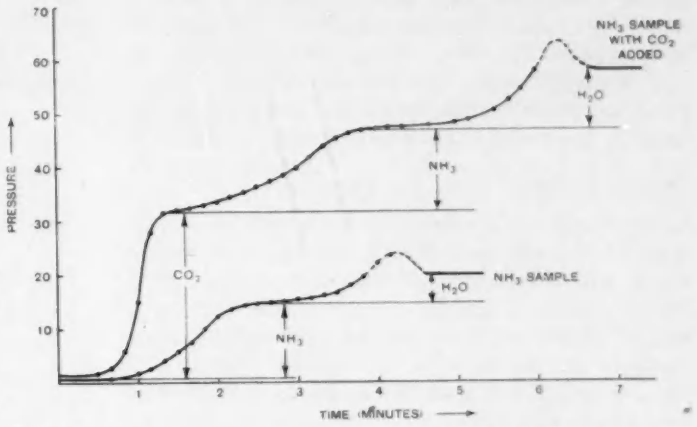

Fig. 3.—Vapour-pressure curve for a standard CO_2—NH_3 mixture.

of air is then directed into the top of the flask, and as soon as the last visible liquid air has evaporated, a stop-watch is started and a pressure–time curve obtained by means of the Pirani gauge. To identify a particular constituent, a little of the suspected vapour is introduced into the system from the standard supplies, and the curve re-determined. An increase in an observed branch of the partial–pressure curve by an amount corresponding to the pressure added serves to identify the presence of that particular vapour.

This technique thus involves a purely arbitrary rate of heating of the condensate; the experimental refinement which is necessary to obtain a uniform and measured rate of temperature rise in the side tube is not usually justified.

Types of vapour–pressure curves obtained in practice are shown in figs. 2 and 3, which show the separation of CO_2, SO_2 and H_2O, and CO_2, NH_3 and H_2O respectively. The distinction between the different branches of the curves is well marked in these particular examples and the proportion of each gas present may readily be determined.

A word must be said here about adsorption of gases on the walls of the apparatus. This is inappreciable with the permanent gases, but may reach serious proportions with the more condensable vapours. The adsorption is in some cases considerably reduced by baking out the glass walls of the analytical system at 300°—400°C. prior to admission of the sample, but this procedure is rather inconvenient, and considerably limits the design of the apparatus. Blank tests with known samples will

* Intern. Crit. Tables Vol. I, p. 61 gives a comprehensive table of freezing agents for very low temperatures.

indicate whether the error arising from this source is sufficient to vitiate the analytical results.

The dotted portions of the curves in figs. 2 and 3 are characteristic of water vapour at low pressures (10^{-4}—10^{-2} mm.) and are due to the fact that the vapour, as it evaporates from the side tube, is immediately re-adsorbed to a large extent on the walls of the apparatus. For this reason, the determination of water vapour by low pressure methods is not usually reliable, and is not included in the procedure to be described.

THE DETERMINATION OF HYDROGEN.

A standard method for the determination of H_2 and CO when both are present is to admit an excess of oxygen and then allow the gases to react at a heated platinum filament; alternatively the gases may be oxidised by means of a heated copper filament previously coated with oxide. The CO_2 and water vapour formed are then determined by differential freezing.

The avidity with which water vapour is adsorbed by glass, referred to above, is a serious objection to this method. In addition, the oxidation of CO at an oxidised copper filament only proceeds to completion at a very slow rate.

TABLE II.

Determination of H_2 by diffusion through palladium tube.

Gases introduced (microns)	H_2 found (microns)
11.1 H_2 } 20.3 CO }	11.2
37.3 H_2 } 12.8 CO }	37.3

A method which has been found to give very good results for the determination of hydrogen is that of diffusion through a heated palladium tube. The use of this in macro-analysis has been described by A. G. Fleiger,[6] who found that it is, within certain limits, quite satisfactory for the estimation of hydrogen in the presence of CO. These limits are dictated by the following reactions which occur at the tube surface:

$$2\,CO \longrightarrow C + CO_2 \quad . \quad . \quad . \quad (1)$$

$$CO + 3H_2 \longrightarrow CH_4 + H_2O \quad . \quad . \quad (2)$$

At low pressures (below 0·1 mm.) these reactions do not interfere with the analysis. A small palladium tube, heated to 700°—800°C. by means of a miniature electric furnace, will remove all the hydrogen from an analytical system of total volume 1,000 c.c. in 10—15 minutes, when the initial pressure is less than 0·1 mm. As is shown by the results quoted in Table II, the presence of CO does not interfere with the test.

With a sample consisting of CO only, and with a side tube on the apparatus cooled with liquid air to freeze out CO_2, the palladium tube may be heated for prolonged periods without any measurable diminution in pressure, showing that decomposition of the CO according to equation (1) is not appreciable under these conditions.

The CO left may then be determined by burning with oxygen at a platinum filament. A useful method

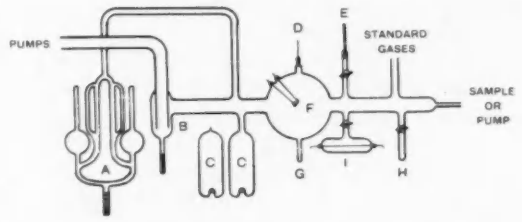

Fig. 4.—Apparatus for the micro-analysis of gases.

for the introduction of oxygen into the analytical system is by diffusion through a silver tube attached to the system. The tube is heated in air to a temperature of about 700°C., when oxygen, and none of the other constituents of the atmosphere, is able to diffuse in. This method is recommended by J. B. Taylor,[7] and is very satisfactory, since it enables an amount of oxygen just in excess of that required to be admitted into the system. The oxygen is quite pure.

THE SEPARATION OF NITROGEN FROM INERT GASES.

The determination of nitrogen in the presence of argon or other inert gas may be carried out by absorption with calcium heated to redness. A more efficient method is absorption of the nitrogen by means of a tantalum filament; this has been discussed by D. A. Wright,[8] who showed that provided the filament is previously cleaned by flashing at over 2,000°C., in a good vacuum, nitrogen is cleaned up very rapidly by tantalum at temperatures between 1,000° and 1,500°C. Absorption is rapid above 1,200°C., even in the presence of mercury vapour, and it was found possible accurately to determine the percentage of nitrogen in a nitrogen-inert gas mixture by this means.

AN APPARATUS FOR LOW PRESSURE ANALYSIS.

An apparatus for low pressure analysis, incorporating some of the principles discussed above, is shown in fig. 4.

The whole apparatus can be evacuated to a pressure of less than 10^{-5} mm. by means of a diffusion pump, and when blank tests are satisfactory, can be isolated from the pump at the mercury cut-off B. The total volume of the system can be varied within

wide limits by the addition of dead space, but 400—900 c.c. is normally convenient; the volume is readily calibrated by expanding a given pressure of gas from the known volume of the McLeod gauge. It will be noticed that few taps are used in this system; mercury cut-offs are preferable, but the introduction of one or two taps does not give rise to any trouble, provided Apiezon grease is used to lubricate them.

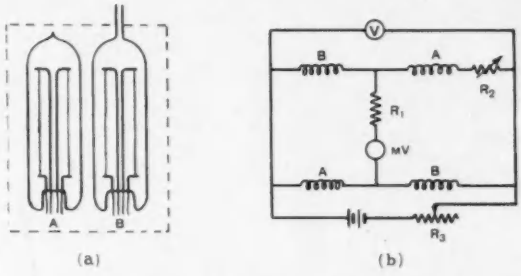

Fig. 5.—(a) Pirani gauge and (b) electrical arrangement for deflection method.

The two McLeod gauges A, shown mounted in parallel, cover a pressure range from 10^{-5} to 5 mm., the fine gauge reading up to 0·1 mm. and overlapping with the coarse gauge. The Pirani gauge C has a restricted linear range up to 0·03 mm. and will be described more fully later. Pressure readings are normally taken on both gauges, and the specific response of the Pirani gauge provides a useful check during the analysis.

For such work as the determination of the gases evolved from heated metals, a second pump is incorporated which removes the gases continuously from the sample and delivers them directly into the analytical system as indicated. F. J. Norton and A. L. Marshall,[9] in their work on the degassing of metals, tested the transmission of various gaseous mixtures through a diffusion pump and found that there is no observable reaction with the hot mercury. A real difficulty arises from the continuous evolution of water vapour from the pump under these conditions, and this can only be avoided, as is done by the above authors, by previously baking the apparatus. For externally collected samples, however, the second pump can be dispensed with and the sample is introduced into the system by a suitable cut-off.

The palladium thimble D has a wall-thickness of 0·1 mm. and is 50 mm. long by 1·3 mm. diameter. It is silver-soldered to a copper thimble which is joined directly to the glass. Suitable dimensions for the pure silver tube E, which is used for the admission of oxygen, are: 0·2 mm. wall-thickness, 100 mm. long and 2·0 mm. diameter; a tap is used to isolate the tube from the system while oxygen is being diffused in. A small nichrome-wound silica tube furnace is used to heat these tubes. A platinum filament F, a tantalum strip filament in a separate bulb I, and two freezing-out tubes G and H complete the system.

THE PIRANI GAUGE.

As the Pirani gauge may not be generally familiar, a convenient method of using it will be briefly described. Fig. 5 gives a sketch of the gauge and its associated electrical circuit. The gauge consists of two identical bulbs, each containing two coiled tungsten filaments of as nearly as possible the same resistance (approximately 15 ohms). The filaments are not supported, and hence the instability (associated with variable thermal contacts) which occurred in the older squirrel-cage type is eliminated. The compensating bulb A is highly evacuated and sealed off, while the bulb B is connected to the system. A and B are strapped together and enclosed in a draught-proof cover. The filaments are arranged in a simple bridge circuit as in fig. 5(b); a small variable resistance of 1 or 2 ohms (R_2) enables any zero adjustment to be made and the bridge balanced. A constant voltage is maintained across the bridge, and the pressure up to 0·03 mm. is a linear function of the out-of-balance measured by a high resistance millivoltmeter, the sensitivity of which can be adjusted by a series resistance R_1.

The gauge is calibrated directly, for the separate gases to be measured, by means of the McLeod gauge, it being borne in mind that the latter is liable to serious errors when used with the more condensable gases, owing to condensation on the walls of the bulb and capillary. NH_3 and SO_2 are particularly troublesome in this respect. The calibration is usually carried out in the presence of mercury vapour, since this does not interfere with the operation of the gauge for normal purposes.

Very little zero drift is experienced with this type of gauge, unless it is inadvertently exposed to the atmosphere while in operation; it is readily re-stabilized by flashing the filaments to about 1,600°C. in a good vacuum.

EXPERIMENTAL ANALYSIS.

The experimental procedure for the analysis of a mixture presumed to contain H_2, O_2, CO, CO_2, N_2 and argon may now be illustrated.

The system is pumped out, and the platinum filament, tantalum filament, and the palladium and silver tubes are thoroughly degassed by heating at appropriate temperatures. Pressure readings are then taken after each of the following operations:

(1) Sample admitted. Freezing trichlorethylene on H.

(2) Liquid air on H. Tap on H closed, thus isolating condensable gas present.

(3) Liquid air on G. Platinum filament glowed for 2 minutes.

(4) Palladium tube heated at 700° C. until pressure constant. (Normal time about 10 minutes).

(5) Excess oxygen admitted through silver tube.

(6) Platinum filament glowed for 2 minutes.

(7) Residual oxygen removed by admitting excess hydrogen through palladium tube, glowing platinum filament, and finally heating palladium tube.

(8) Tantalum filament heated at 1,200°C. until pressure constant. (Normal time about 10 minutes).

(9) System pumped out, and CO_2 condensed during combustion measured by replacing the liquid air on G with freezing trichlorethylene.

(10) System pumped out again, and condensable gas in H investigated by means of a vapour pressure-time curve.

Data obtained during an actual analysis were :

Operation	Pressure (microns)	Operation	Pressure (microns)
(1)	20·0	(6)	11·1
(2)	11·2	(7)	5·2
(3)	11·2	(8)	0·1
(4)	10·3	(9)	CO_2 = 5·3
(5)	19·2	(10)	CO_2 = 8·5

which give

CO_2 from (1) and (2) $= 8{\cdot}8$

and from (10) $= 8{\cdot}5$

O_2 from (3) and (2) $=$ nil

H_2 from (4) and (3) $= 0{\cdot}9$

CO from (5) and (6) $= \frac{2}{3} \times 8{\cdot}1 = 5{\cdot}4$

from (7) and (4) $= 5{\cdot}1$

and from (9) $= 5{\cdot}3$

and the residual gas from (8) and (7) is principally N_2. The percentage composition of this sample was therefore taken as

CO_2 $(\frac{8.5}{20.0} \times 100) = 42{\cdot}5\%$

O_2 $=$ nil

H_2 $(\frac{0.9}{20.0} \times 100) = 4{\cdot}5\%$

CO $(\frac{5.3}{20.0} \times 100) = 26{\cdot}5\%$

N_2 Remainder

To test the accuracy of the method a given sample of burnt coal-gas was analysed by the technique described above, and the composition of the gas was checked by macro-analysis. The results, which are given in Table III, indicate that the accuracy is well within the limits normally required.

DETERMINATION OF MINOR CONSTITUENTS.

An example may be given of the use of analysis at low pressures for the determination of impurities in a gas, *viz.*, the determination of traces of CO and CO_2 in certain samples of air collected from a furnace atmosphere. For this, a large sample of about 1 c.c. was taken and the pressure read on the coarse McLeod gauge. The CO_2 was then frozen out, and the remaining gas pumped away. The amount of CO_2 present could then be determined by means of the Pirani gauge or fine McLeod. For the determination of CO a similar portion was taken, the CO_2 frozen out and isolated by means of the tapped side tube; the platinum filament was then run for about five minutes with liquid air on the second side tube. The CO_2 formed by oxidation could then be determined in the same way as before.

The oxygen present was determined on smaller samples of approximately 0·03 c.c., by introducing excess hydrogen through the palladium tube, burning the platinum filament, with a side tube cooled in liquid air, and then diffusing out the unburnt hydrogen. The following results are typical of those obtained :

	Composition per cent.		
CO	0·55	0·54	0·55
CO_2	0·43	0·50	0·42
O_2	20·4	20·3	
N_2	Remainder		

The oxygen figure is in good agreement with that expected.

DETERMINATION OF CARBON AND OXYGEN IN METALS.

Finally, one may refer to the advantages of the low pressure method for the determination of carbon in metals. Details of the analysis by this method of carbon in iron and iron alloys containing less than 0·1 per cent carbon have been published by N. A. Zeigler.[9] Specimens weighing a few grams are heated in pure oxygen in a vacuum apparatus, and the resulting gases drawn over heated copper oxide. The CO_2 formed is condensed out, the apparatus thoroughly evacuated and the volume of CO_2 then measured by means of a McLeod gauge. The reproducibility in a regular analysis is $\pm$ 0·0005 per cent for a two-gram sample, but with extra precautions this can be greatly reduced, so that a reproducibility of $\pm$0·0001 per cent is possible. By heating first at 600° and then at 1,050°C. a ready distinction may be made between carbon present

TABLE III.

Method of Analysis	Vol. of sample taken	Composition per cent.				
		CO_2	O_2	H_2	CO	N_2
Macro-analysis. Hahn's modified Orsat apparatus	51·4 c.c.	5·6	Nil	14·1	9·25	Remainder
Low pressure	·0159 c.c.	5·5	Nil	13·5	10 9	Remainder
	·0157 c.c.	5·3	Nil	14·6	9·5	Remainder

on the surface and in the body of the metal, since the rate of diffusion of carbon from the interior to the surface is quite inappreciable at the lower temperature.

A similar technique has been found to be very useful in the qualitative analysis of the surface films formed on metals under various conditions. Oxide, sulphide and carbonaceous films are quickly distinguished by treating in a low pressure of hydrogen, or oxygen, and analysing the gaseous products.

The determination of oxygen in metals offers greater difficulties. If the metal is heated in hydrogen, and the resultant pressure of water vapour measured, care must be taken to ensure that clean-up of water vapour is not appreciable. W. A. Baker[11] has described an apparatus in which the water vapour is measured at a pressure of several millimetres by trapping it in a small volume. Under these conditions absorption is small and the results given indicate that a high order of accuracy is then possible.

A large amount of work has been done on the determination of oxygen in steels by the so-called vacuum-fusion method[12], in which a sample of the steel is melted in a gas-free graphite crucible, and the oxygen content is calculated from the volume of carbon oxides produced. Even oxides as refractory as alumina are fully reduced by this procedure, so that all the oxygen present in the sample is determined. Most investigators in this field rely on standard micro-chemical methods (*e.g.*, modified Orsat methods) for the analysis of the gases collected, but there would appear to be considerable scope here for the application of low pressure technique.

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G.E.C. "Osira" Lighting in a Prominent Factory.

The main machine bay of a well-known factory illuminated by 400 watt "Osira" lamps mounted in dispersive reflectors. G.E.C. "Osira" mercury vapour discharge lamps are used exclusively for the lighting of this factory. In all, more than 300 of these lamps are employed.

An Electrically Operated Clay Gun for a Blast Furnace.

By A. F. MORGAN, A.M.I.E.E.,
G.E.C. Cardiff Branch.

In the following article a detailed description is given of the electrically operated clay gun —the first of its kind to be installed in Great Britain—which successfully solves the problem of stopping the tapping hole of a blast furnace at the conclusion of a cast, without disturbing the continuity of operation.

GENERAL.

THE production of iron from a modern blast furnace is a continuous process, and the main essential of furnace operation is therefore smooth and regular working of the furnace with as few stops as possible. For many years the most difficult problem with which the operator has been faced has been the development of a satisfactory method of stopping the tapping hole at the conclusion of the cast, without upsetting the normal working of the furnace.

The introduction of the electrically operated clay gun into this country is a revolutionary solution to this problem, and the first gun of this type has been installed on one of the blast furnaces at the Cardiff works of Guest, Keen & Baldwin's Iron and Steel Co., Ltd.

Each of these furnaces has an output of 3,000/3,500 tons a week. Ore and coke are drawn from storage bunkers, located at the back of the furnaces, into scale cars, on which the weight of the charge is recorded, and it is then emptied from the scale car hopper into skips. The skips are hoisted to the top of the furnace, where they are automatically emptied by means of an electrically operated double skip hoist. The charging process is virtually continuous, and frequently proceeds whilst casting is in progress.

Blast is provided from turbo-blowers and enters the furnace through ten nozzles or tuyeres, at pressures up to 18 lbs. per sq. in. The air is pre-

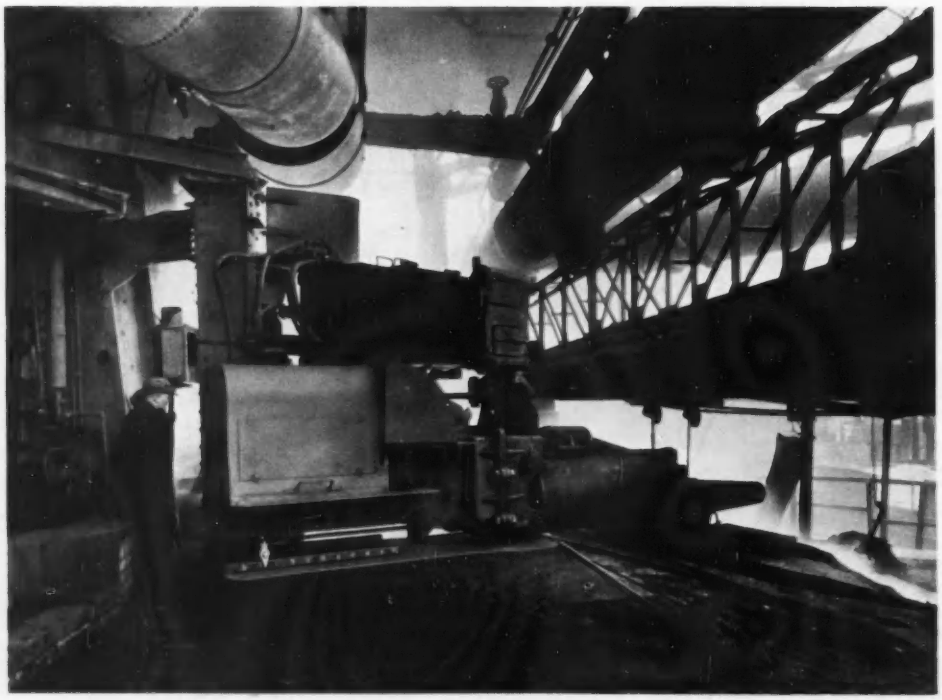

Fig. 1.—The electrically operated clay gun installed at one of the blast furnaces of Guest, Keen & Baldwin's Iron and Steel Co., Ltd., at their Cardiff Works.

heated in vertical stoves before entering the furnace.

Iron is drawn from the furnace at approximately six-hourly intervals. The cast is begun by drilling a passage through the clay plug in the tapping hole, and a normal cast occupies about half an hour, up to 150 tons of iron being obtained in this period, after which the hole is plugged with clay.

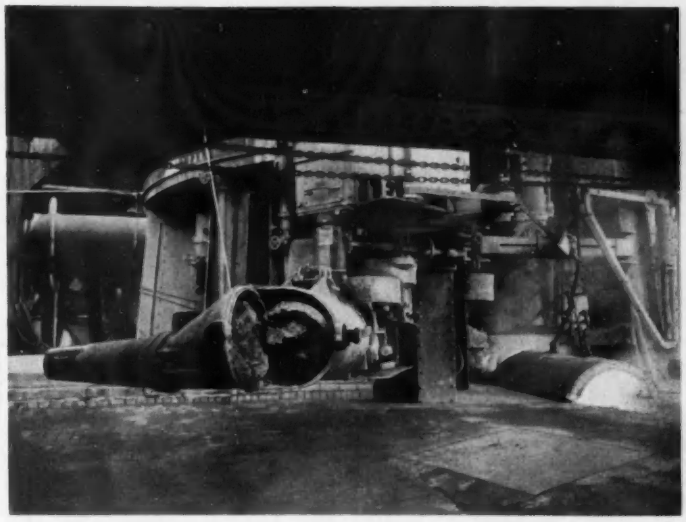

Fig. 2.—Gun nozzle opened, showing clay in the barrel. The cast has just begun.

STEAM OPERATED CLAY GUN.

The original plugging equipment consisted of a steam operated plunger type gun suspended from a boom, the gun being swung into position by the operators and continuously charged by hand until sufficient clay had been forced into the tapping hole. About fifty strokes of the plunger were necessary, the operation taking about ten minutes. Throughout the whole of this period the men were exposed to the intense heat from the runners and the danger of a "blow-back."

In order to carry out this operation, the furnace was first allowed to run dry, it being both difficult and dangerous to stop the hole against the flow of iron. The blast pressure was then taken off the furnace in order to allow the operators to approach the tapping hole.

This enforced removal of the blast pressure caused a "stiffening" of the furnace, or a sudden collapsing of the stock inside, and generally from half-an-hour to two hours elapsed before normal working conditions were restored.

ELECTRICALLY OPERATED CLAY GUN.

With the installation of the electrically operated gun, these difficulties and other attendant troubles were at once removed. The action of the gun is positive, and it is therefore unnecessary to reduce the blast pressure when plugging the hole. This leads to smooth melting and movement of the stock in the furnace, giving greatly increased production and also a steady supply of gas, which is used for stove and furnace heating throughout the works. It is also found that the life of the furnace lining is enhanced, tuyere maintenance reduced, and that there is a reduction in the waste due to the formation of flue dust.

The gun is capable of plugging the hole against the flow of iron, so that any desired quantity of iron may be tapped at any given time, or the cast may be terminated immediately in the event of an emergency. The entire plugging operation takes but fifteen seconds, which allows no time for the clay to harden, so that a greater quantity can be injected, resulting in a longer tapping hole; also the clay remains softer, thus reducing the labour in drilling the next hole.

In addition, a most important advantage is the greater safety afforded the furnace personnel, as the gun is remote controlled.

The gun was built under license to E. C. Brosius, of the United States. Fig. 1 shows the gun in the "out" position. The clay is contained in the barrel at the front end, which has a capacity of 10 cubic feet or about half a ton of clay. The clay

Fig. 3.—Gun in the plugging position showing details of suspension and adjustment.

is forced through the nozzle by means of a piston in the barrel, a maximum pressure of about 35 tons being exerted upon it by a double rack and pinions, the latter being driven through a reduction gearing by a motor located in the cubicle at the rear of the gun. Beneath the motor can be seen a scale, graduated in cubic feet, which indicates the amount of clay forced into the tapping hole, a normal quantity being 6 cubic feet. Fig. 2 shows the nozzle swung open, enabling the clay to be seen. The gun is partly charged in this way, the balance of the clay being added through the hatch on the top of the barrel when the nozzle has been closed.

Fig. 4.—View of clay gun immediately after the conclusion of the plugging operation.

The gun is suspended from a boom, which in turn is mounted on a column sunk into the platform and tied back to the furnace structure. A second motor is mounted inside the boom and drives a double sheave winch through reduction gearing. Attached to the winch are two flat steel wire ropes—the "pull-in" and "pull-out" ropes, which can be seen in figs. 2 and 3—one of which pays out as the other is wound in. The ropes pass over suitable loose pulleys, and swing the gun into position. Correct adjustment of the gun to locate the nozzle in the tapping hole is obtained by means of the hand wheel and connecting rod seen beneath the boom, and the round steel wire rope above the pull-out rope.

The gun in the plugging position prior to a cast being taken is shown in fig. 3, while the photograph reproduced in fig. 4 was taken immediately after the conclusion of plugging.

While the duty cycle of the plant is very short, the utmost reliability is essential. It was therefore decided to adopt as power units three-phase squirrel cage induction motors with direct-to-line contactor starting, no overload releases or other protective relays of any description being employed. However, both motions were provided with limit switches and brakes to guard against the possibility of mechanical

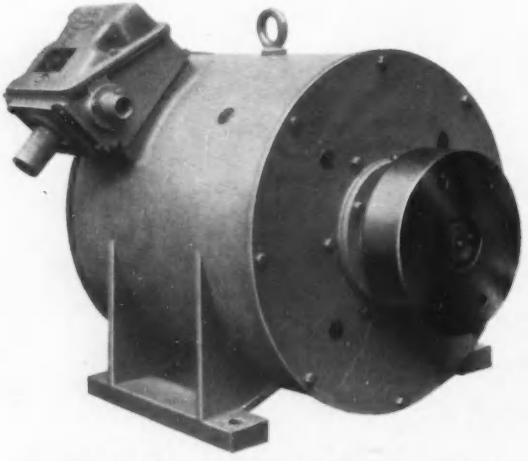

Fig. 5.—20 h.p. totally enclosed squirrel cage induction motor, 400 volts, 3 phase, 50 cycles, 550 r.p.m., for operating the gun.

Fig. 6.—Wound stator of the 20 h.p. gun motor, showing method of insulating the windings.

damage due to faulty operation of the controllers.

The duty of the motors is particularly arduous, both being subjected to very high ambient temperatures, some idea of which may be obtained by examination of fig. 4. The gun remains above the iron runner, still containing molten iron and slag, until the clay has hardened.

The boom motor has to be capable of remaining stalled on full voltage in order to hold the gun against

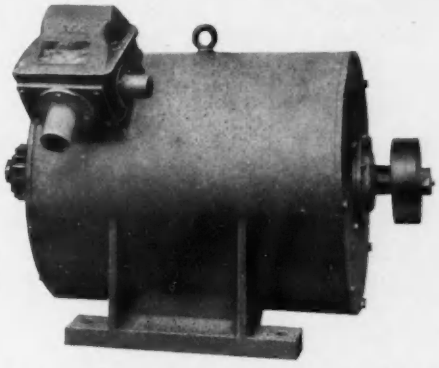

Fig. 7.—10 h.p. totally enclosed squirrel cage induction motor, 400 volts, 3 phase, 50 cycles, 550 r.p.m., for operating the boom.

the tapping hole during plugging, and the gun motor may be called upon to stall if the tapping hole is particularly small.

The manufacture of the motors was entrusted to The General Electric Co., Ltd. The gun motor is nominally rated at 20 h.p., 550 r.p.m. and the boom motor at 10 h.p. at 550 r.p.m., both on a half-hourly basis, with a temperature rise of 50 degs. C. The motors give stalling torques of 1·6 and 1·35 times full load torque respectively, each taking 2·5 times full load current from the line at full voltage. These conditions can be maintained for half a minute without excessive heating.

The robust mechanical construction of the machines is illustrated in figs. 5 and 7. Welded steel construction has been employed throughout, the shafts being machined from 3 per cent nickel steel, and carried in cartridge type heavy duty ball and roller bearings. The rotor cores are secured to the shafts by two deep keys at right angles.

The stator windings consist of asbestos insulated conductors laid in mica lined slots, the overhang being doubly lapped with mica and asbestos tapes (fig. 6). The rotor windings are also of special construction (fig. 8). Bars of bronze are secured in semi-

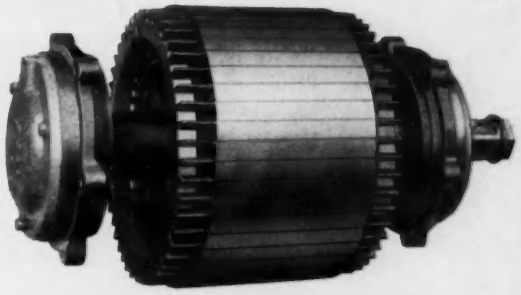

Fig. 8.—Wound rotor of the 20 h.p. gun motor, illustrating insulation of the bars and details of construction.

enclosed slots lined with anodised aluminium, which projects ¼in. at either end of the core. The end rings are of heavy section Eureka, and are slotted to receive the rotor bars, thus allowing a large joint area. The whole is brazed together at high temperature. This construction combines high heat capacity with high resistance.

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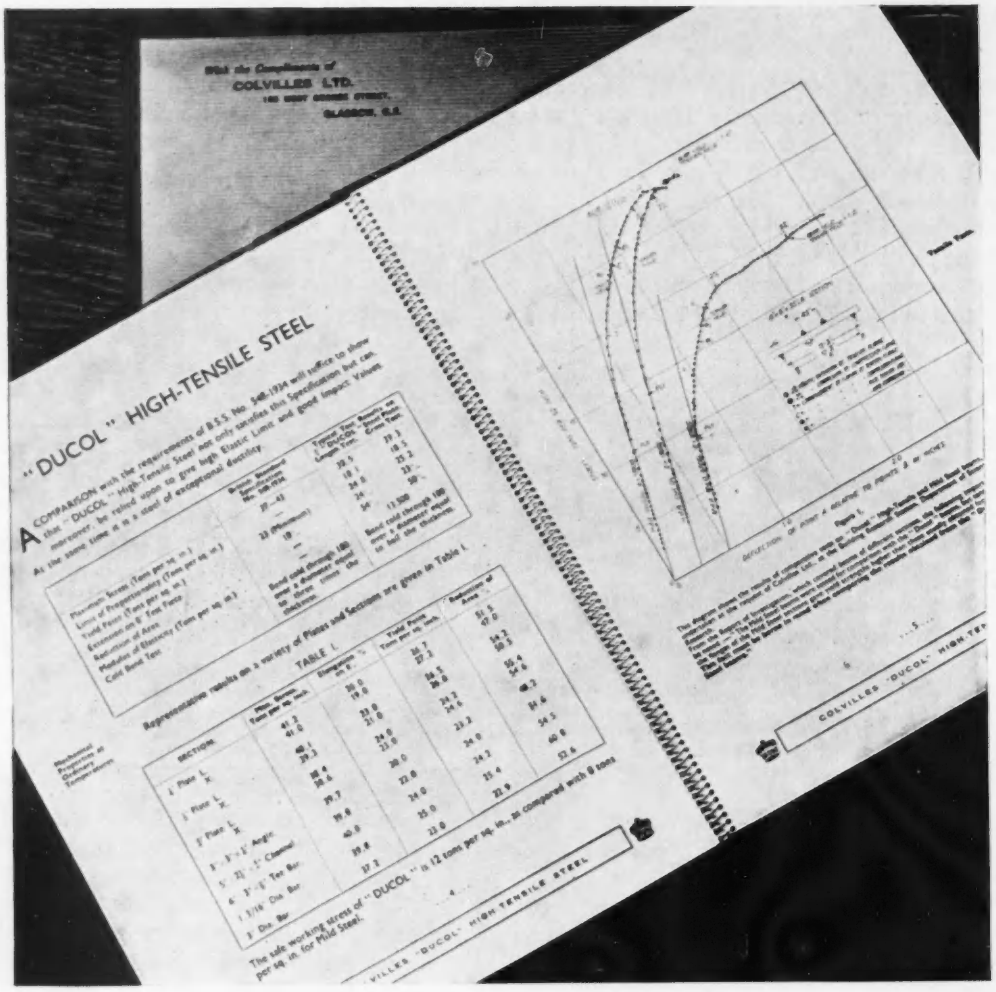

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